Well-to-Wheels Energy Use and Greenhouse Gas Emissions of Plug-In Hybrid Electric Vehicles Using GREET - Phase II Analysis

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Scope of Argonne's PHEV WTW Analysis: Vehicle Powertrain Systems and Fuel Pathways

- Vehicle powertrain systems:
  - Conventional international combustion engine vehicles (ICEVs)
  - Regular hybrid electric vehicles (HEVs)
  - Plug-in hybrid electric vehicles (PHEVs) with all electric range (AER) of 10-40
    - ✓ Internal combustion engines (ICEs)
    - ✓ Fuel cells (FCs)
  - Electric vehicles (EVs)
- Fuel options:
  - Petroleum
    - ✓ Gasoline
    - ✓ Diesel
  - E85 with ethanol from
    - ✓ Corn
    - ✓ Switchgrass
  - Electricity:
    - ✓ Marginal generation mixes in four regions
    - ✓ Average generation mixes of the U.S., CA, and Northeast U.S.
  - Hydrogen
    - ✓ Distributed production from NG-SMR
    - ✓ Central production from switchgrass

Argonne's Phase 1 PHEV WTW Analysis (Feb. 2009):

- PHEV performance evaluation
  - ✓ Fuel economy results for the average technology improvement in PSAT were used
  - ✓ Did not assume on-road degradation for electricity consumption in CD mode
  - ✓ Did not adjust design AER to on-road AER
  - ✓ Split design for all PHEVs
- Electricity generation for PHEVs: relied on an ORNL study
  - ✓ Key features of the study
    - Marginal generation mix for 25% of on-road vehicles as PHEVs by 2030
    - Either early or late evening charging with three charging rates
    - No capacity expansion for PHEV load
  - ✓ ANL included five generation mixes for PHEV recharge
    - Three marginal generation mixes from ORNL study
    - US average mix
    - A renewable case

Argonne's Phase 2 WTW Analysis Addresses PHEV Key Issues in Details

- PHEV performance evaluation
  - *Split design for PHEV10 and 20; series design for PHEV30 and 40*
  - *Calculated on-road adjusted fuel economy for each mode of operation*
  - *Calculated on-road adjusted AER*
- PHEV mileage shares by power source
  - *Determined VMT shares by grid power and on-board power from on-road AER*
- In-house simulations of electricity generation mixes in different utility regions to charge PHEVs
  - *Distributed EIA's national vehicle stock projections to states*
  - *Analyzed distribution of vehicles by last trip ending time for each region*
  - *Generated PHEVs load profiles in each region for three charging scenarios*

Fuel and Electricity Consumption of PHEVs

PSAT Simulation Results Were Processed for This Analysis

- PSAT fuel economy simulations results for these vehicle types were used
  - ICEV: Gasoline SI, E85 SI, Diesel CI
  - HEV: Gasoline SI, E85 SI, Diesel CI; Hydrogen FC (250 mi on UDDS)
  - PHEV: Gasoline SI, E85 SI, Diesel CI; Hydrogen FC
  - EV (150 mi on UDDS)

- PHEV configuration options
  - Split configuration for AER of 10 and 20 miles (FC-PHEVs are series hybrids)
  - Series configuration for AER of 30 and 40 miles

- MY 2015 midsize car was considered in this analysis

- Though PSAT results were with technology improvements for low, average, and high scenarios, the results for the low-improvement scenario were used in this analysis in order to be consistent with EIA baseline projections

- Lab-based fuel economy values from PSAT were adjusted to on-road values for this analysis

- PHEV miles driven by grid electricity and on-board power
  - On-road AER, instead of design AER, was used
  - Data from the 2001 National Household Travel Survey was employed to estimate daily VMT share of PHEVs in CD mode (utility factor)

PSAT Lab-Based Fuel Economy Results (Miles of Gasoline Equivalent Gallon, Wh/Mile for Electric Operation)

Unadjusted Wh/mi and mpgge			AER 0	AER 10 Split Design			AER 20 Split Design			AER 30 Series Design			AER 40 Series Design		
			Regular Hybrid	CD Electric	CD Engine	CS Engine	CD Electric	CD Engine	CS Engine	CD Electric	CD Engine	CS Engine	CD Electric	CD Engine	CS Engine
Gasoline ICE	UDDS	30.5	55.2	191	222	60.7	193	206	60.25	244	250	41.2	254	555	40.5
	HWFET	44.9	49.1	212	98.6	53.7	211	132	53.21	262	850	42.1	264	1030	41.6
E85 ICE	UDDS		51.4	191	208	56.6	192	192	56.2	244	232	38.2	254	512	37.5
	HWFET		45.7	212	91.5	49.8	211	123	49.5	262	796	39.5	264	974	39.0
Diesel ICE	UDDS		57.9	198	238	60.8	202	203	60.5	248	274	43.9	256	577	43.2
	HWFET		51.1	223	101	53.1	214	135	52.9	267	1100	43.0	266	1150	42.6
H_2 FC	UDDS		72.8	210	211	75.4	214	196	74.4	244	457	72.8	248	877	71.6
	HWFET		75.9	248	139	75.8	255	645	75.0	262	1510	73.3	264	1290	72.5
EV	UDDS	267													
	HWFET	274													

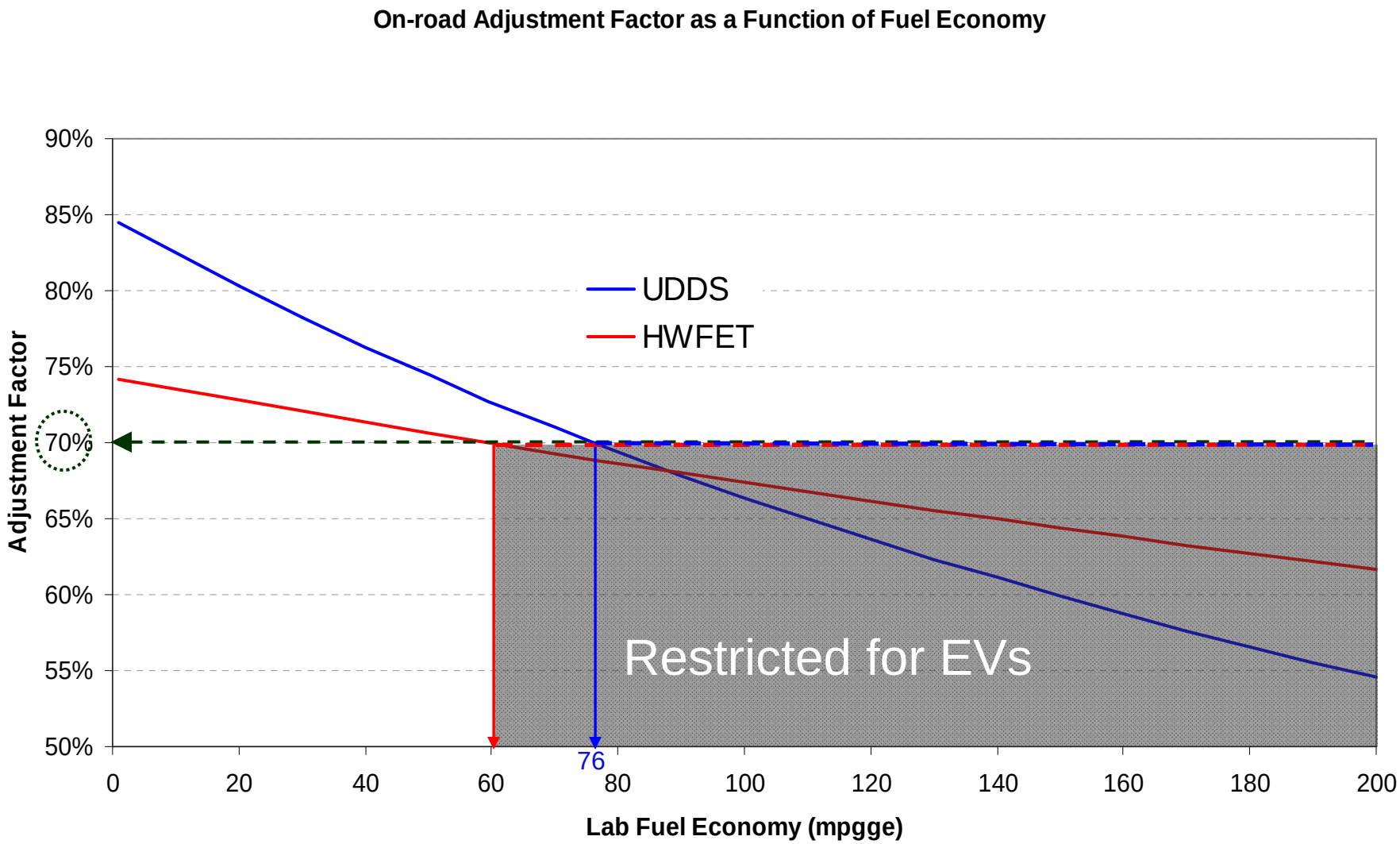
- CD Electric = charge depleting operation with grid electricity
- CD Engine = charging depleting operation with on-board power systems (ICE Engine or Fuel Cell)
- CS = charge sustaining operation with on-board power systems
- UDDS = Urban Dynamometer Driving Schedule; HWFET = Highway Fuel Economy Test

Note: PSAT included after-treatment thermal efficiency penalty to the diesel fuel economy

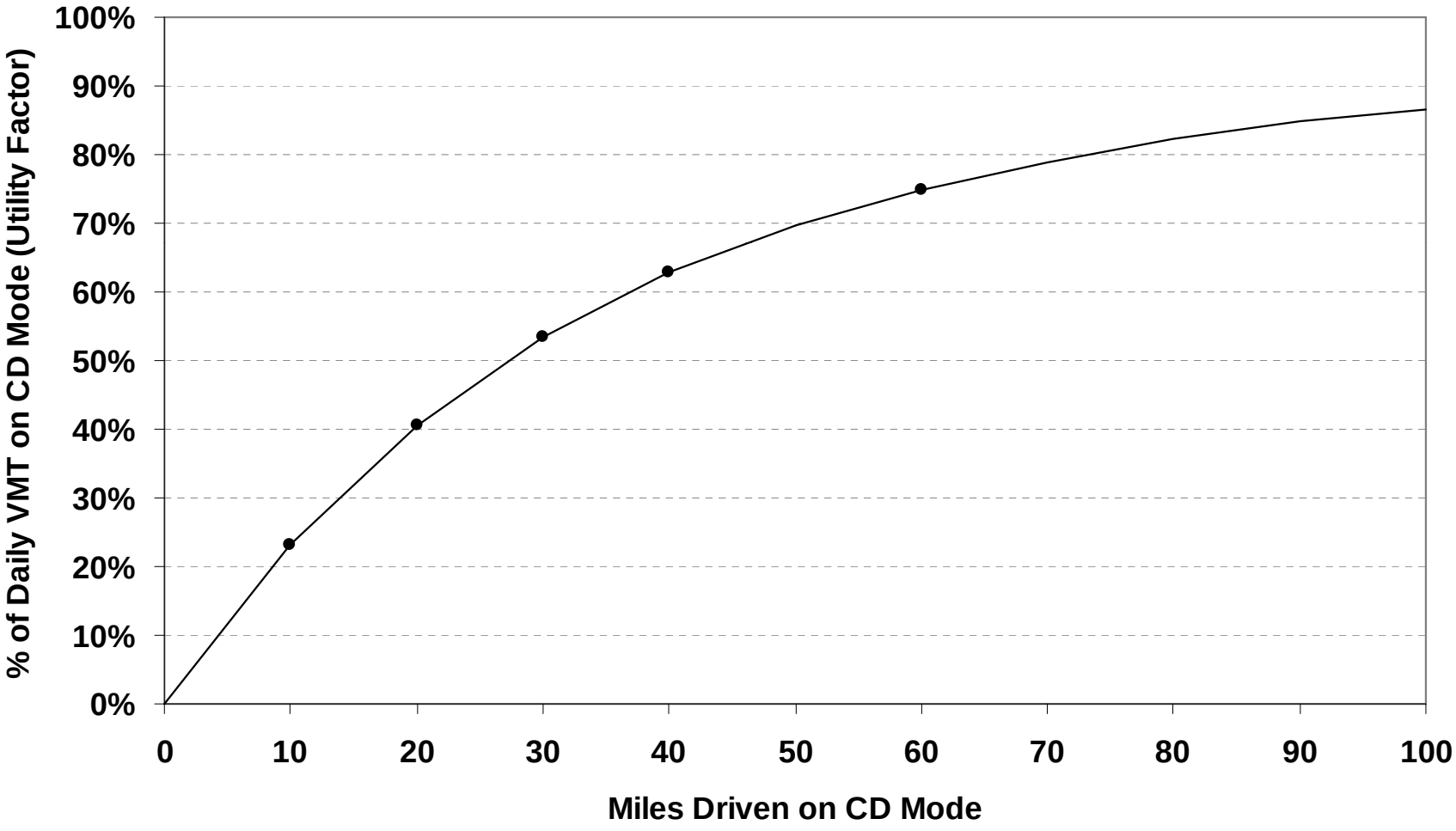
Processing of PSAT Fuel Economy Results for GREET WTW Simulations

- Lab-based fuel economy for ICEs and fuel cells was adjusted to on-road fuel economy according to EPA's MPG-based formulae
- For EVs and CD mode of PHEVs with battery electricity, an adjustment method has yet to be defined. We employed EPA's suggested adjustment factor of 70% to the equivalent fuel economy of EVs and CD mode (both electric and ICE) of PHEVs
- On-road AER of PHEVs is adjusted to be 70% of design AER
- The city (UDDS) and highway (HWFET) results were combined with 43% UDDS and 57% HWFET, the EPA new split
- Charging efficiencies of 83%, 86%, and 87% for charging through 220V/20A (AER 40) , 110V/20A (AER 30), and 110V/15A (AER 10 and 20) were applied to PSAT battery output-based electricity consumption for EVs and CD Electric
- PSAT fuel consumption for charge depleting and charge sustaining operations were combined using the utility factor (UF)
  - $(FC_{CDGrid} + FC_{CD_{ICE}})* UF + FC_{CS} * (1-UF)$

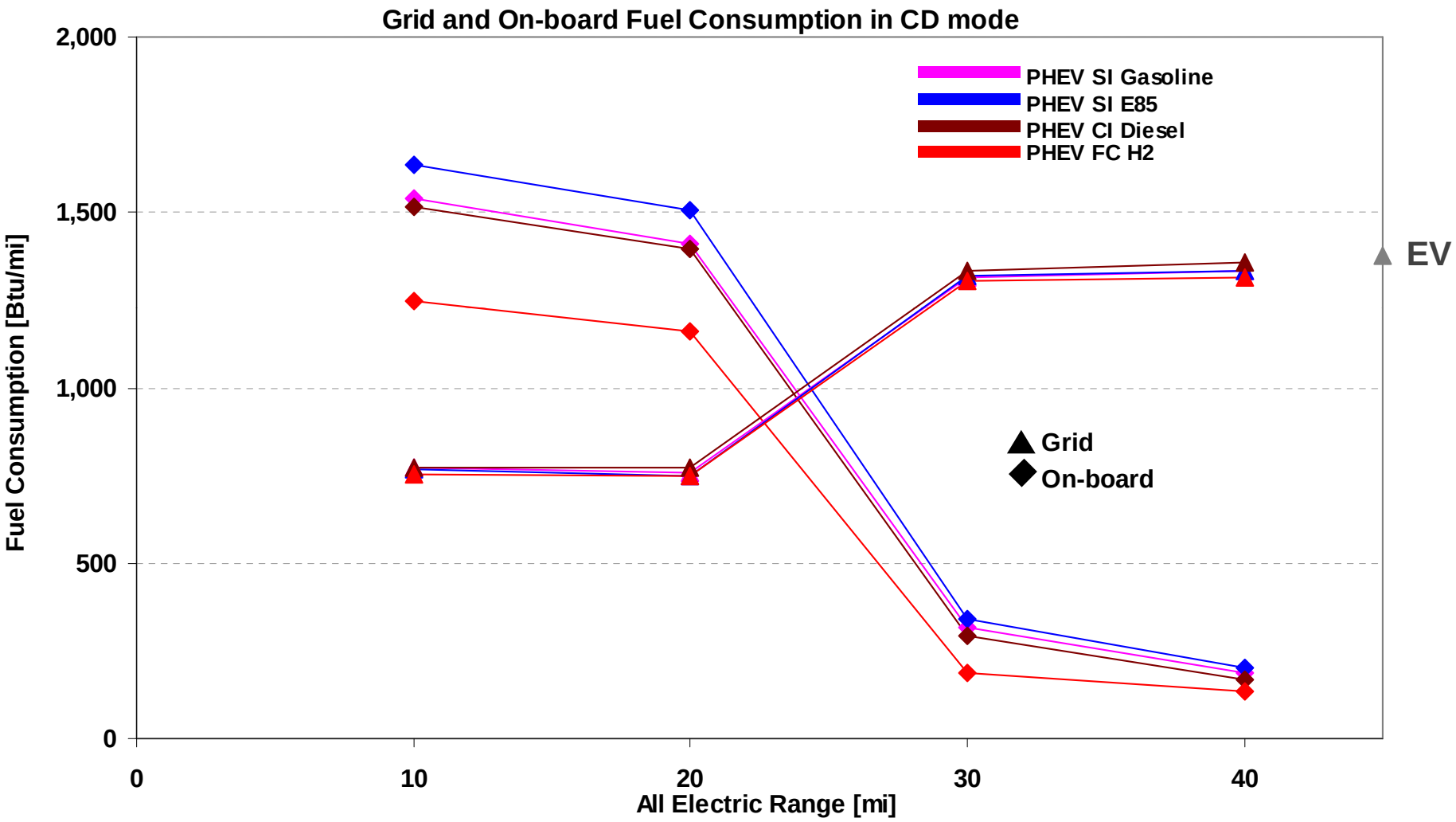
On-Road Adjustment Factor for Lab Fuel Economy: EPA's MPG-Based Formulae



PHEVs with 20-Mile on CD Mode Account (on the average) For 40% of Daily VMT, PHEVs with 40-Mile More than 60%

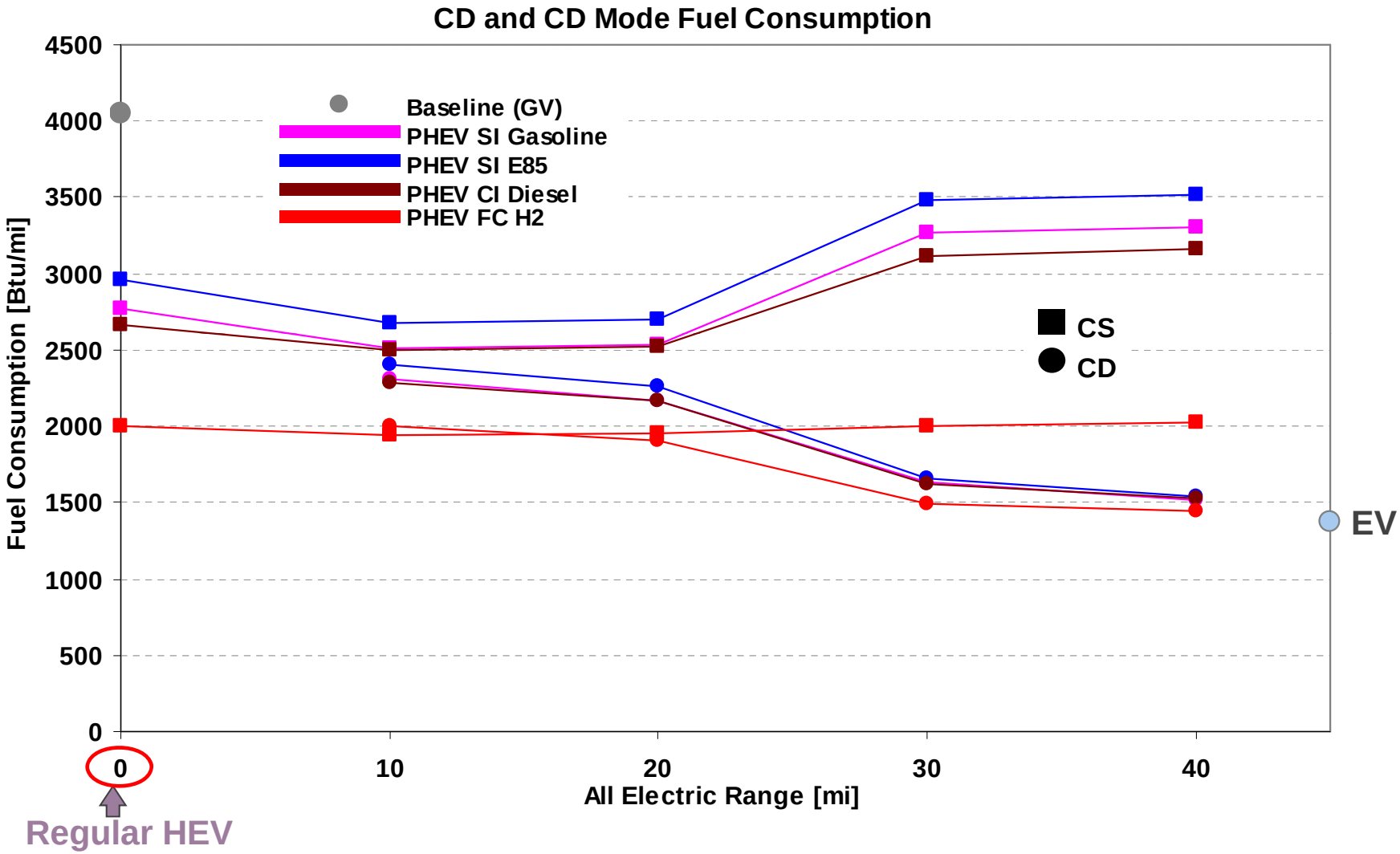


On-road Fuel Consumption by Technology and AER: Grid and On-board Energy Use Under the CD Operation



Note: the two energy sources are combined to serve a given mile.

On-road Fuel Consumption by Technology, Mode, and AER



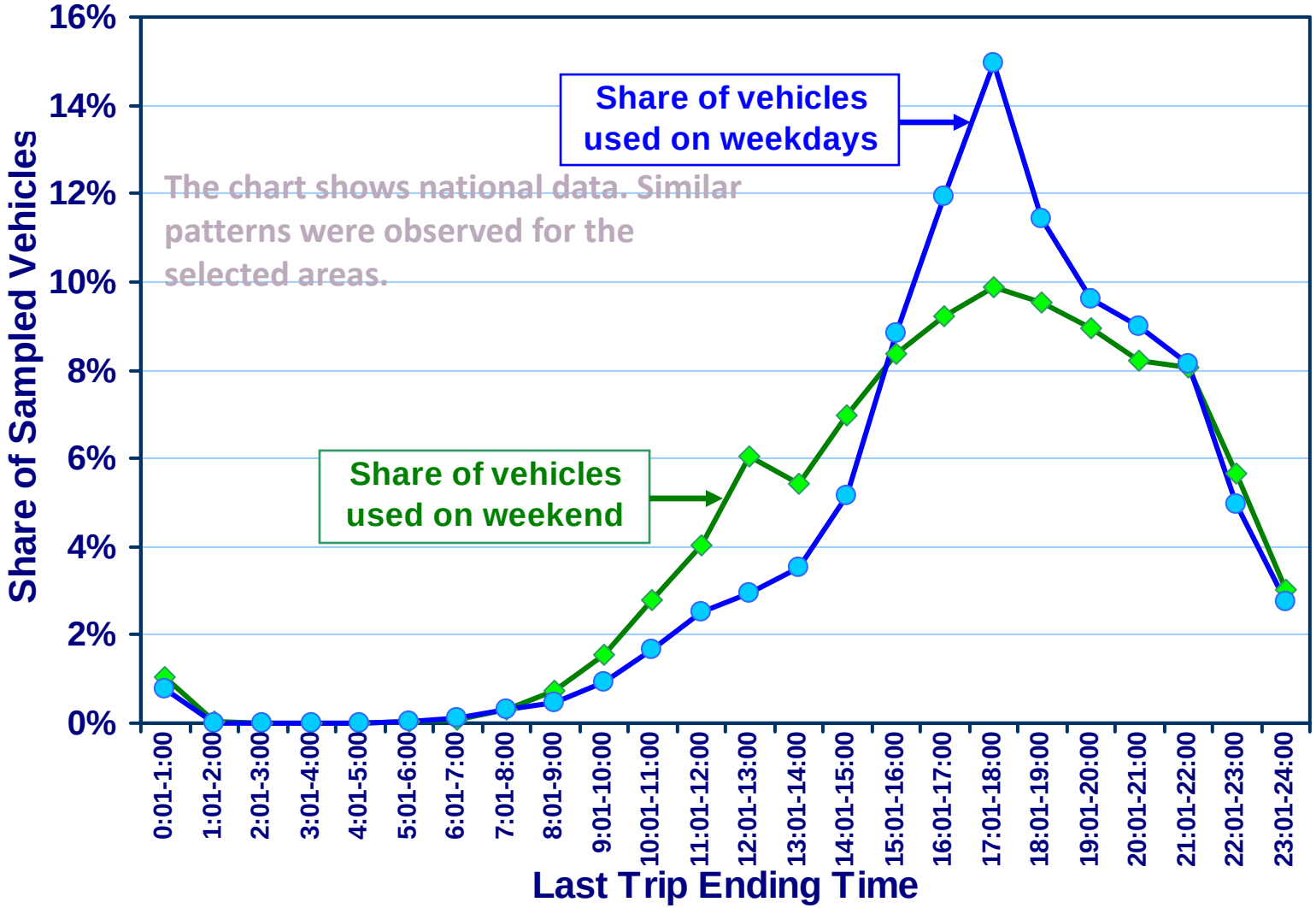
Electric Load Profiles with and without PHEVs

Key Factors Determining Electricity Generation Mix to Charge PHEVs Are Considered in ANL Phase 2 Analysis

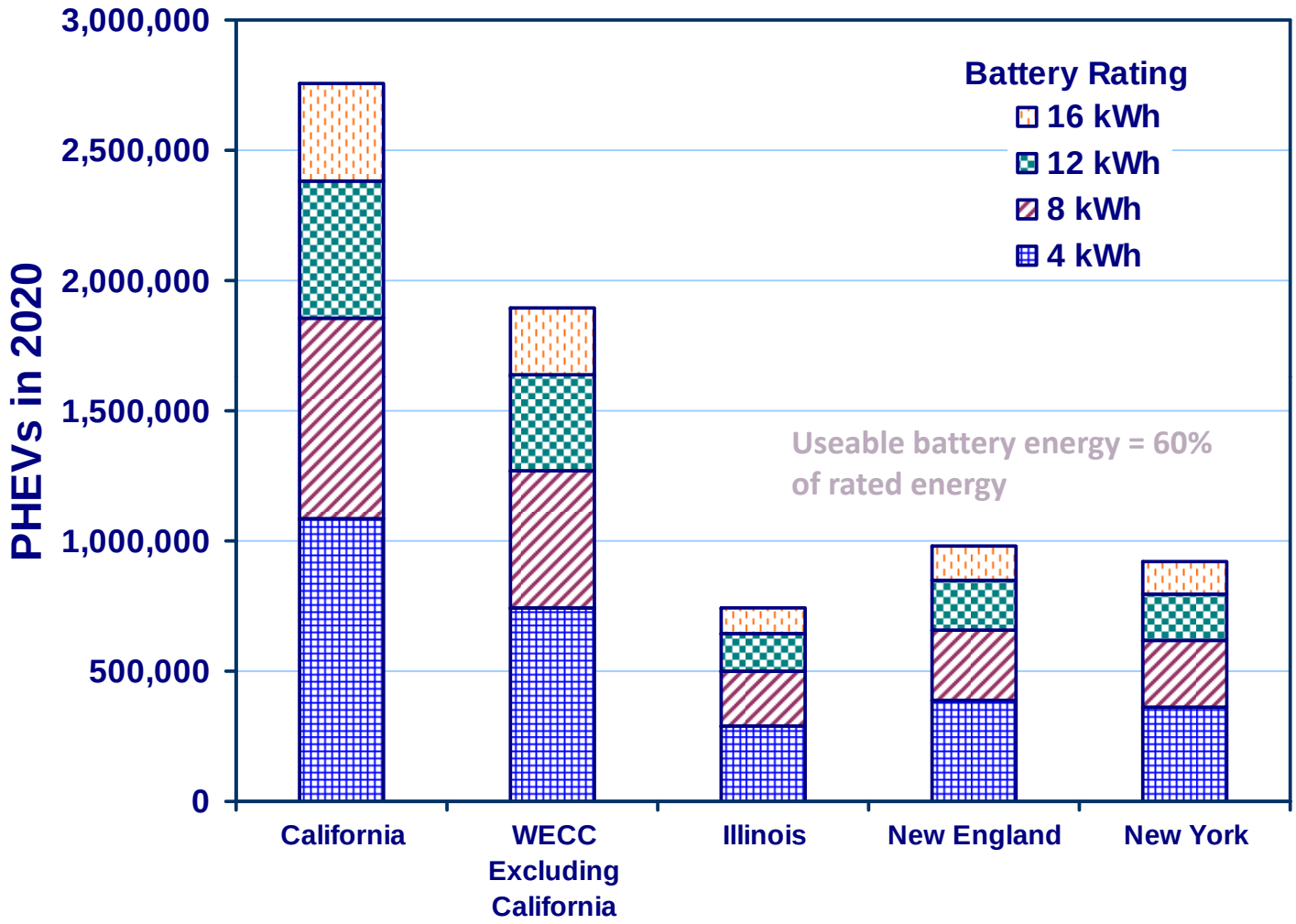
- What is the total electric load from PHEVs?
  - PHEV market penetration: 10% on-road fleet for 2020 (30% for 2030 not completed)
  - Distribution of AER and vehicle class of PHEVs (battery useable energy)
  - One full charge per day per PHEV
- What time of the day are PHEVs being charged?
  - Three charging scenarios were developed
    - ✓ *Unconstrained charging: charging begins at the last trip ending time*
    - ✓ *Alternative charging scenarios*
      - *Smart charging (filling valley of load during off-peak hours)*
      - *Delaying PHEV charging by 3 hours*
- Implications of electric generation capacity in a given region
    - ✓ *NE-ISO*, NY-ISO, IL, WECC, CA, WECC excluding CA*
- Specific generating units to be dispatched for PHEV charging to determine marginal generation mix for PHEVs

*ISO=Independent System Operator (coordinates, controls and monitors the operation of the electrical power grid)

Weekday Last Vehicle Trip Ending Time Shows a Peak At 5-6 PM



10% of Cars and SUVs In 2020 Were Assumed As PHEVs, Allocated With AER 10, 20, 30, and 40 Using NHTS Travel Pattern



Key assumptions of PHEV market shares: PHEV10 – 39%; PHEV20 – 29%; PHEV30 – 19%; PHEV40 - 13%

Techniques Used to Model Electric Power System Dispatch

- New York and New England Independent System Operators (ISOs)
  - Thermal power plants modeled at unit level by a probabilistic dispatch model on an hourly basis, which accounts for the probability of forced outage of the different generation units
  - Non-dispatchable systems, such as wind and non-storage hydro power generators, cannot be independently controlled, and thus were excluded from dispatch modeling
  - Transmission system not modeled; therefore transmission constraints were not considered
- Western Electric Coordinating Council (WECC)
  - Optimizes power system operations (for minimum cost) within physical and institutional constraints; such as, plant capacities, reserve margins, unit ramp rates, hydropower energy limits, among others
  - Simulates hourly power system operation chronologically
  - Transmission system is modeled by developing a network of nodes and links representing groups of loads and generators. Total transfer capabilities limit power transfers between nodes
- State of Illinois
  - Transmission system is modeled at bus (i.e., transmission line) level. Constraints on power transfers
  - Thermal power plants modeled at unit level and are connected to specific bus
  - Simulates power system operation in hourly time steps

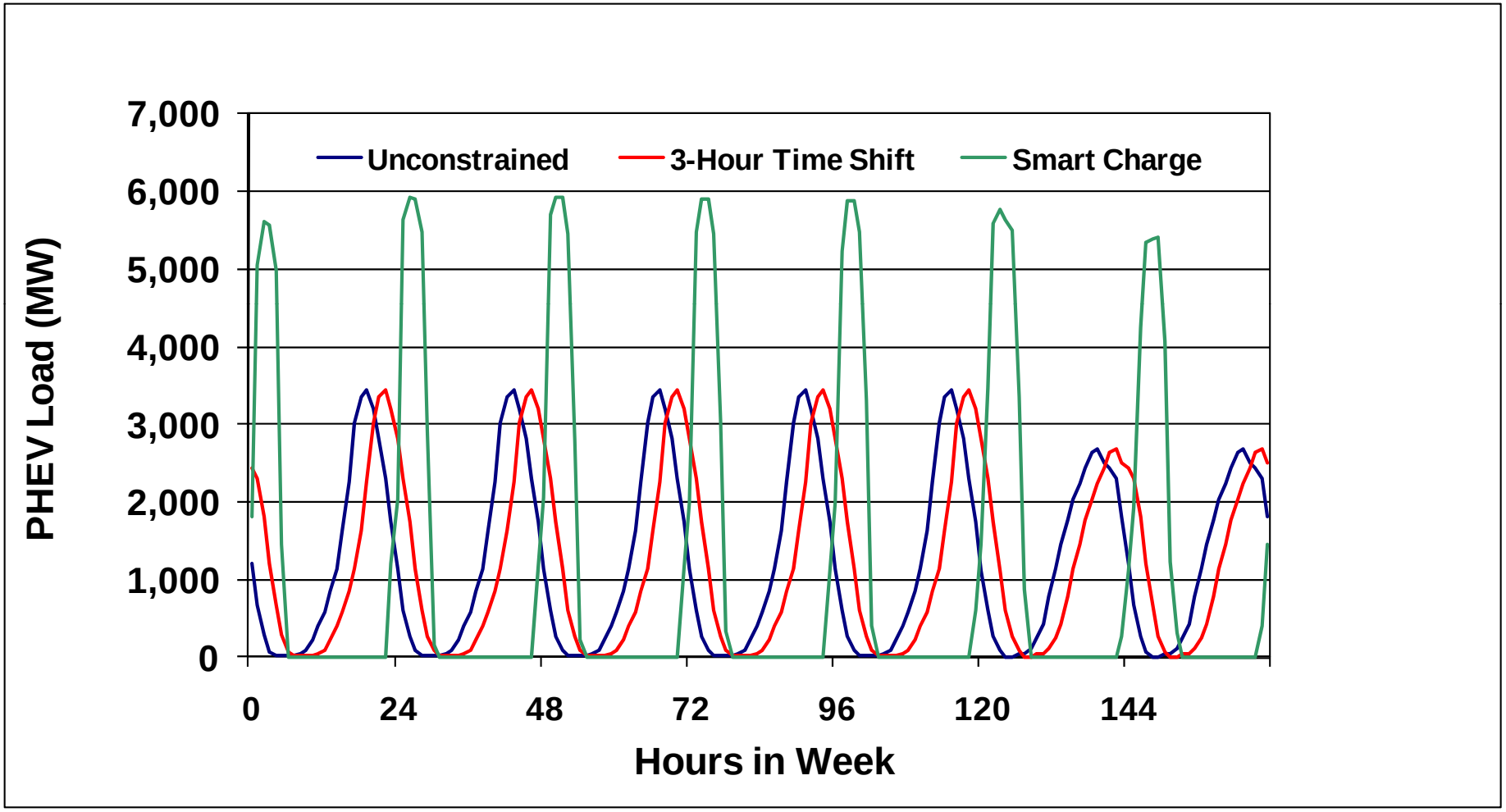
Capacity Responsibility of PHEV Loads in 2020

- Power systems in the U.S. typically use planning reserve margin (RM) of 15-18%
- Customer loads that increase system peak load require additional generating capacity to be added to the system
- For each of the analyzed systems, the needs for new generating capacity in 2020 were estimated based on the actual contribution of PHEV loads to the system peak load and the need to maintain a 15% planning RM
- The technology choices and unit sizes for new capacity additions were based on the considerations of their costs and type of duty required by additional PHEV loads
- In the end, after new capacity additions, PHEV loads in 2020 will be served by the entire system, not just by the new capacity additions

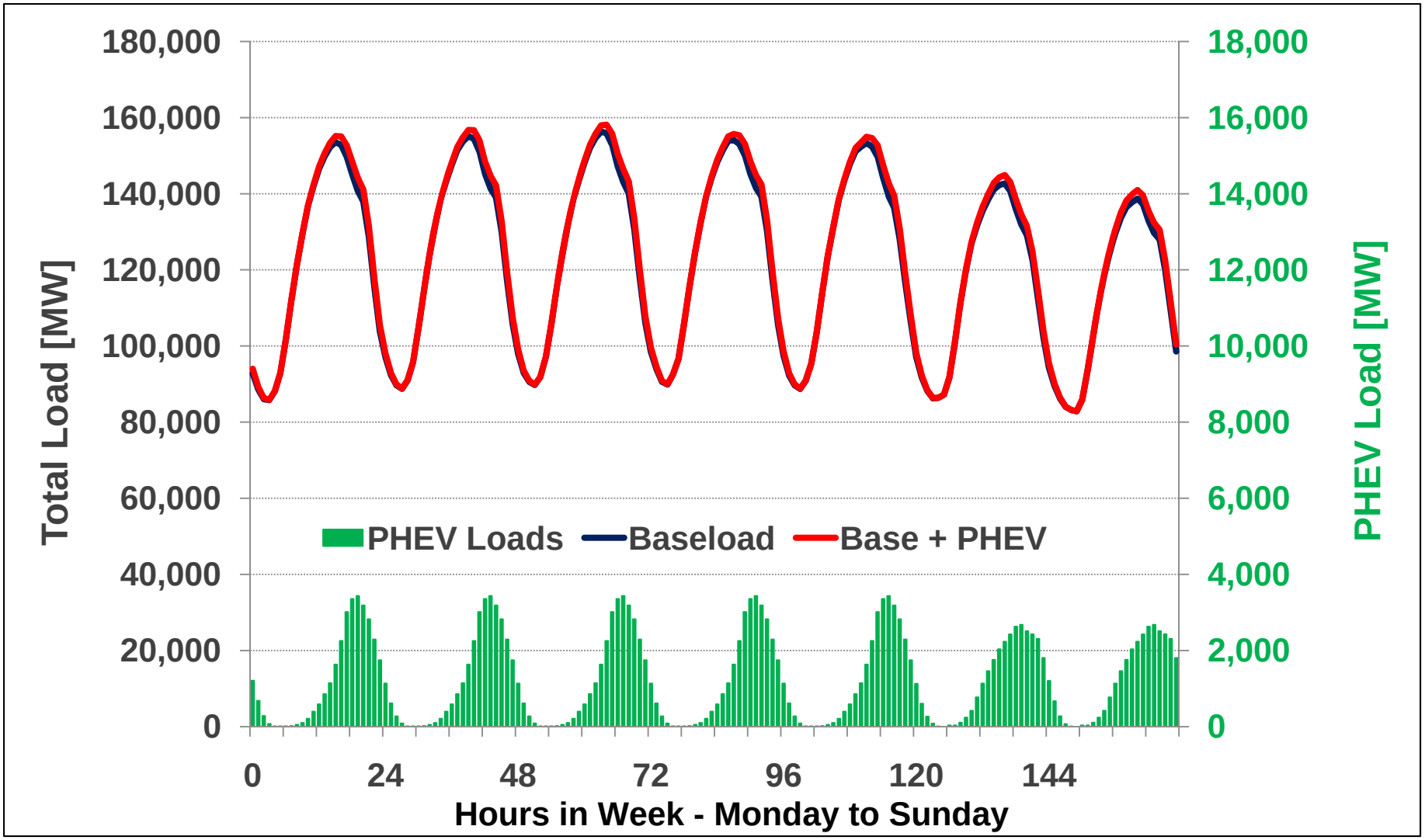
New Capacity Requirements in 2020 due to PHEV Loads

Power System	System Peak Load (MW)	Unconstrained Charge			Constrained Charge			Smart Charge		
		Max. PHEV Load (MW)	System Peak Increase (MW)	New Capacity Addition (MW)	Max. PHEV Load (MW)	System Peak Increase (MW)	New Capacity Addition (MW)	Max. PHEV Load (MW)	System Peak Increase (MW)	New Capacity Addition (MW)
NY-ISO	38,738	685	370	NGCC 400	685	181	GT 230	1,286	0	0
NE-ISO	31,292	759	513	NGCC 400 + GT 230	759	169	GT 230	1,373	0	0
WECC	156,325	3,807	1,819	NGCC 5x400	3,807	589	NGCC 2x400	5,935	0	0
Illinois	38,749	563	336	NGCC 400	563	178	GT 230	1,028	0	0

Comparison of PHEV Load Profiles – Typical WECC Summer



WECC Load Profile for a Typical Summer Week in 2020 Unconstrained Case



2020 Generation Mixes for PHEV Recharge - Unconstrained Charging (with Added Capacity to Cover PHEV Load)

	NE-ISO				NY-ISO				IL			
	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**
Coal												
Utility Boiler / IGCC	21,147	21,147	0	**0.0%**	20,980	20,980	0	**0.0%**	95,213	97,237	2,023	**67.2%**
Natural Gas												
Utility Boiler	190	179	-11	**-0.5%**	20,359	20,092	-266	**-12.7%**	156	177	20	**0.7%**
Combined Cycle	68,502	70,770	2,268	**102.0%**	58,781	61,183	2,401	**114.5%**	3,087	3,768	680	**22.6%**
Simple Gas Turbine	3,716	4,230	514	**23.1%**	4,649	4,576	-73	**-3.5%**	4,249	4,512	264	**8.8%**
Residual Oil												
Utility Boiler	5,552	5,020	-532	**-23.9%**	2,422	2,445	23	**1.1%**	195	231	36	**1.2%**
Nuclear	31,787	31,787	0	**0.0%**	42,835	42,835	0	**0.0%**	74,658	74,672	13	**0.4%**
Biomass												
Utility Boiler / IGCC	7,646	7,644	-2	**-0.1%**	25,553	25,552	0	**0.0%**			0	**0.0%**
Other												
Renewable	6,756	6,744	-12	**-0.6%**	25,976	25,987	12	**0.6%**	37,082	37,054	-28	**-0.9%**
Total	145,298	147,521	2,224	**100.0%**	201,554	203,651	2,097	**100.0%**	214,641	217,650	3,009	**100.0%**

	CA + Import				WECC w/o CA				WECC Total			
	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**
Coal												
Utility Boiler / IGCC	21,890	20,141	-1,749	**-27.6%**	302,633	304,458	1,826	**42.0%**	324,522	324,599	77	**0.7%**
Natural Gas												
Utility Boiler	40,886	41,641	755	**11.9%**	4,597	4,601	4	**0.1%**	45,483	46,242	759	**7.1%**
Combined Cycle	129,989	136,819	6,830	**107.7%**	11,303	13,793	2,490	**57.3%**	141,292	150,612	9,320	**87.2%**
Simple Gas Turbine	7,471	8,019	548	**8.6%**	1,049	1,072	23	**0.5%**	8,521	9,091	571	**5.3%**
Residual Oil												
Utility Boiler	0	0	0	**0.0%**	0	0	0	**0.0%**	0	0	0	**0.0%**
Nuclear	37,719	37,701	-18	**-0.3%**	40,375	40,375	0	**0.0%**	78,094	78,076	-18	**-0.2%**
Biomass												
Utility Boiler / IGCC	3,594	3,571	-23	**-0.4%**	245	245	0	**0.0%**	3,839	3,816	-23	**-0.2%**
Other												
Renewable	99,677	99,677	0	**0.0%**	207,661	207,661	0	**0.0%**	307,338	307,338	0	**0.0%**
Total	341,226	347,570	6,345	**100.0%**	567,863	572,205	4,342	**100.0%**	909,089	919,776	10,686	**100.0%**

2020 Generation Mixes for PHEV Recharge - PHEV Recharged Delayed for 3 Hrs (with Added Capacity to Cover PHEV Load)

	NE-ISO				NY-ISO				IL			
	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**
Coal												
Utility Boiler / IGCC	21,147	21,147	0	**0.0%**	20,980	20,980	0	**0.0%**	95,213	97,007	1,794	**77.8%**
Natural Gas												
Utility Boiler	190	194	4	**0.2%**	20,359	20,585	226	**10.8%**	156	173	16	**0.7%**
Combined Cycle	68,502	69,755	1,253	**56.3%**	58,781	58,973	192	**9.2%**	3,087	3,363	275	**11.9%**
Simple Gas Turbine	3,716	4,463	746	**33.6%**	4,649	6,270	1,621	**77.7%**	4,249	4,449	200	**8.7%**
Residual Oil												
Utility Boiler	5,552	5,771	219	**9.8%**	2,422	2,469	48	**2.3%**	195	221	27	**1.2%**
Nuclear	31,787	31,787	0	**0.0%**	42,835	42,835	0	**0.0%**	74,658	74,667	8	**0.4%**
Biomass												
Utility Boiler / IGCC	7,646	7,651	4	**0.2%**	25,553	25,552	0	**0.0%**			0	**0.0%**
Other												
Renewable	6,756	6,754	-2	**-0.1%**	25,988	25,986	-1	**-0.1%**	37,082	37,066	-15	**-0.7%**
Total	145,298	147,522	2,224	**100.0%**	201,566	203,651	2,085	**100.0%**	214,641	216,946	2,305	**100.0%**

	CA + Import				WECC w/o CA				WECC Total			
	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**
Coal												
Utility Boiler / IGCC	21,890	19,865	-2,025	**-31.9%**	302,633	305,092	2,460	**56.7%**	324,522	324,958	435	**4.1%**
Natural Gas												
Utility Boiler	40,886	41,688	802	**12.6%**	4,597	4,597	0	**0.0%**	45,483	46,285	801	**7.5%**
Combined Cycle	129,989	136,931	6,942	**109.4%**	11,303	13,210	1,907	**43.9%**	141,292	150,141	8,848	**82.8%**
Simple Gas Turbine	7,471	8,193	722	**11.4%**	1,049	1,025	-24	**-0.6%**	8,521	9,218	698	**6.5%**
Residual Oil												
Utility Boiler	0	0	0	**0.0%**	0	0	0	**0.0%**	0	0	0	**0.0%**
Nuclear	37,719	37,676	-43	**-0.7%**	40,375	40,375	0	**0.0%**	78,094	78,051	-43	**-0.4%**
Biomass												
Utility Boiler / IGCC	3,594	3,540	-54	**-0.8%**	245	245	0	**0.0%**	3,839	3,785	-54	**-0.5%**
Other												
Renewable	99,677	99,677	0	**0.0%**	207,661	207,661	0	**0.0%**	307,338	307,338	0	**0.0%**
Total	341,226	347,570	6,345	**100.0%**	567,863	572,205	4,342	**100.0%**	909,089	919,776	10,686	**100.0%**

2020 Generation Mixes for PHEV Recharge - Smart Charging (Filling the Valley)

	NE-ISO				NY-ISO				IL			
	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**
Coal												
Utility Boiler / IGCC	21,147	21,147	0	**0.0%**	20,980	20,980	0	**0.0%**	95,213	96,325	1,112	**99.5%**
Natural Gas												
Utility Boiler	190	194	3	**0.1%**	20,359	20,973	615	**29.5%**	156	156	0	**0.0%**
Combined Cycle	68,502	70,608	2,106	**94.7%**	58,781	59,965	1,184	**56.8%**	3,087	3,087	0	**0.0%**
Simple Gas Turbine	3,716	3,798	81	**3.7%**	4,649	4,927	278	**13.3%**	4,249	4,249	0	**0.0%**
Residual Oil												
Utility Boiler	5,552	5,581	29	**1.3%**	2,422	2,431	9	**0.4%**	195	195	0	**0.0%**
Nuclear	31,787	31,787	0	**0.0%**	42,835	42,835	0	**0.0%**	74,658	74,658	0	**0.0%**
Biomass												
Utility Boiler / IGCC	7,646	7,651	5	**0.2%**	25,553	25,553	0	**0.0%**			0	**0.0%**
Other												
Renewable	6,756	6,756	0	**0.0%**	25,988	25,988	0	**0.0%**	37,082	37,088	6	**0.5%**
Total	145,298	147,521	2,224	**100.0%**	201,566	203,651	2,085	**100.0%**	214,641	215,759	1,118	**100.0%**

	CA + Import				WECC w/o CA				WECC Total			
	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**
Coal												
Utility Boiler / IGCC	21,890	19,353	-2,537	**-40.0%**	302,633	306,638	4,006	**92.3%**	324,522	325,991	1,468	**13.7%**
Natural Gas												
Utility Boiler	40,886	41,524	638	**10.1%**	4,597	4,595	-2	**-0.1%**	45,483	46,119	635	**5.9%**
Combined Cycle	129,989	137,682	7,693	**121.3%**	11,303	11,685	382	**8.8%**	141,292	149,368	8,075	**75.6%**
Simple Gas Turbine	7,471	7,959	488	**7.7%**	1,049	1,006	-44	**-1.0%**	8,521	8,965	444	**4.2%**
Residual Oil												
Utility Boiler	0	0	0	**0.0%**	0	0	0	**0.0%**	0	0	0	**0.0%**
Nuclear	37,719	37,775	56	**0.9%**	40,375	40,375	0	**0.0%**	78,094	78,149	56	**0.5%**
Biomass												
Utility Boiler / IGCC	3,594	3,600	7	**0.1%**	245	245	0	**0.0%**	3,839	3,846	7	**0.1%**
Other												
Renewable	99,677	99,677	0	**0.0%**	207,661	207,661	0	**0.0%**	307,338	307,338	0	**0.0%**
Total	341,226	347,570	6,345	**100.0%**	567,863	572,205	4,342	**100.0%**	909,089	919,776	10,686	**100.0%**

Generation Efficiencies Are Affected by Capacity Factor

	CA+Import				WECC excluding CA+Import				WECC Total			
	Baseline	Smart charge w/o added capacity	Unconstrained w/ added capacity	3hours delayed w/ added capacity	Baseline	Smart charge w/o added capacity	Unconstrained w/ added capacity	3hours delayed w/ added capacity	Baseline	Smart charge w/o added capacity	Unconstrained w/ added capacity	3hours delayed w/ added capacity
Residual Oil-Fired Power Plants												
Utility boiler												
Natural Gas-Fired Power Plants												
Utility boiler	34.7%	35.9%	33.8%	33.8%	30.6%	33.3%	25.3%	N/A	34.2%	35.9%	33.8%	33.8%
Simple-cycle gas turbine	42.4%	38.4%	35.4%	35.4%	40.7%	41.2%	37.5%	41.1%	42.3%	38.1%	35.5%	35.2%
Combined-cycle gas turbine	44.1%	43.7%	38.0%	40.1%	45.5%	51.0%	47.0%	47.7%	44.2%	44.0%	40.1%	41.5%
Coal-Fired Power Plants												
Utility boiler	32.9%	34.1%	34.0%	33.8%	33.8%	33.8%	33.8%	33.7%	33.7%	33.4%	30.2%	33.1%
Biomass Power Plants												
Utility boiler	29.6%	23.8%	25.3%	26.5%	26.3%	26.3%	26.3%	26.3%	29.4%	23.8%	25.3%	26.5%

	NE-ISO				NY-ISO				IL			
	Baseline	Smart charge w/o added capacity	Unconstrained w/ added capacity	3 hours delayed w/ added capacity	Baseline	Smart charge w/o added capacity	Unconstrained w/ added capacity	3 hours delayed w/ added capacity	Baseline	Smart charge w/o added capacity	Unconstrained w/ added capacity	3 hours delayed w/ added capacity
Residual Oil-Fired Power Plants												
Utility boiler	33.4%	35.6%	33.0%	32.5%	33.1%	32.4%	33.8%	34.3%	26.7%	N/A	24.4%	26.9%
Natural Gas-Fired Power Plants												
Utility boiler	31.5%	31.5%	31.5%	31.5%	34.4%	33.2%	33.9%	32.2%	27.0%	27.0%	27.0%	27.0%
Simple-cycle gas turbine	35.2%	35.7%	37.6%	36.6%	34.3%	35.0%	37.7%	36.6%	35.8%	38.0%	34.9%	35.4%
Combined-cycle gas turbine	44.8%	44.4%	46.6%	43.3%	37.4%	34.2%	38.6%	32.8%	50.1%	45.4%	53.0%	46.8%
Coal-Fired Power Plants												
Utility boiler	35.2%	35.2%	35.2%	35.2%	34.5%	34.5%	34.5%	34.5%	32.2%	27.1%	21.4%	22.2%
Biomass Power Plants												
Utility boiler	22.6%	16.0%	12.1%	15.3%	22.7%	22.2%	19.7%	21.5%				

Impact of Average Generation Mixes Was Also Included In Our Analysis (2020)

	U.S. Mix	Northeastern U.S. Mix	CA Mix
Residual oil	1.0%	2.0%	0.0%
Natural gas[1]	18.2%	19.9%	36.8%
Coal	48.6%	28.7%	14.2%
Nuclear power	19.7%	32.0%	19.3%
Biomass	2.6%	6.9%	1.1%
Others (hydro, wind, etc.)	9.9%	10.5%	28.6%

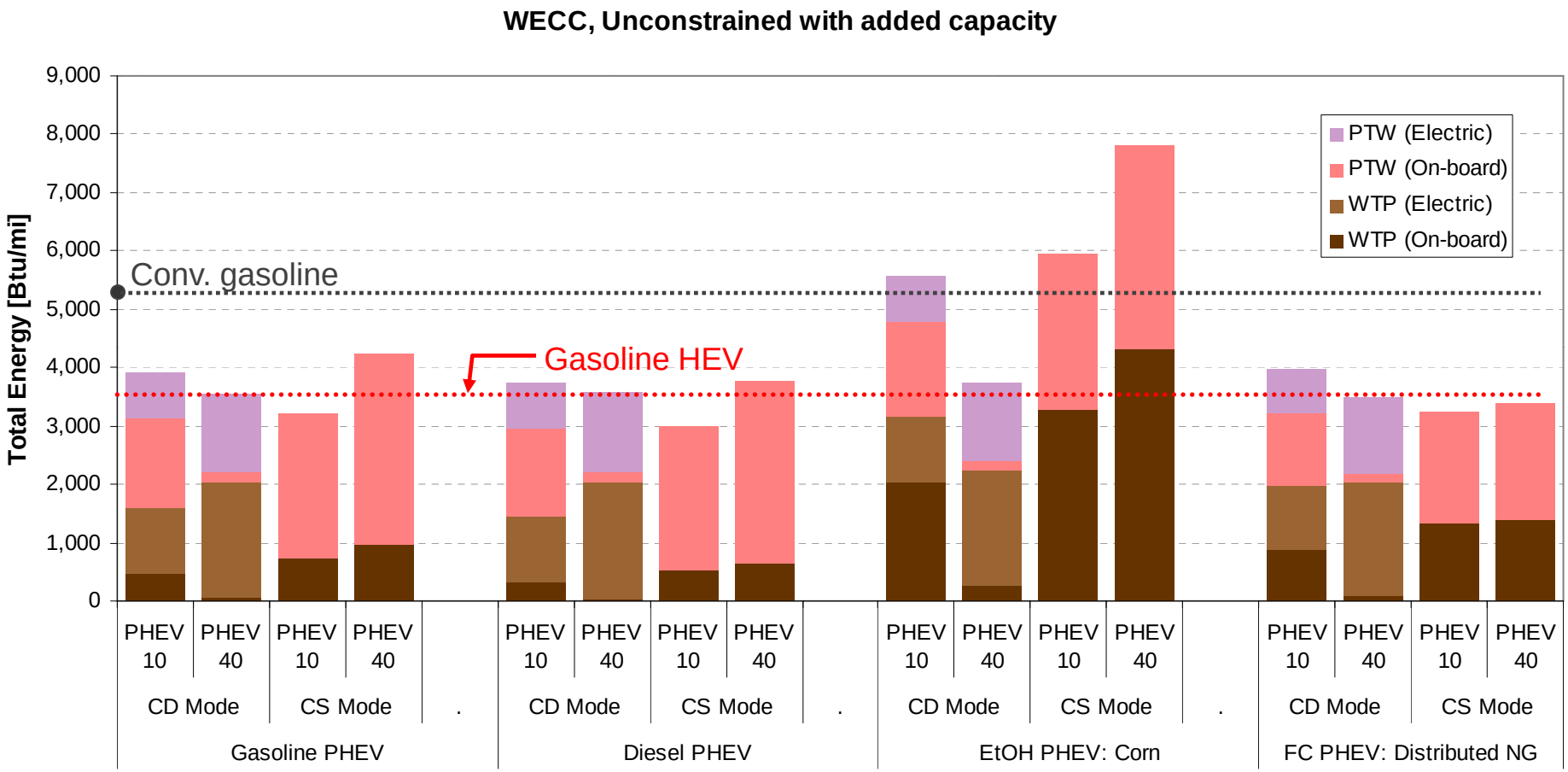
[1]NGCC and simple-cycle shares of total NG power generation are 48% and 38%, respectively

Power Generation Efficiency	GREET default
Residual Oil-Fired Power Plants	
Utility boiler	34.8%
Natural Gas-Fired Power Plants	
Utility boiler	34.8%
Simple-cycle gas turbine	34.8%
Combined-cycle gas turbine	60.0%
Coal-Fired Power Plants	
Utility boiler	34.4%
IGCC	50.0%
Biomass Power Plants	
Utility boiler	32.4%
IGCC	45.0%

T&D Loss	2020
NE-ISO	8.0%
NY-ISO	8.0%
MAIN (Illinois)	6.8%
WECC-Total	9.4%
CA+Import	9.7%
WECC excluding CA+Import	9.3%
USA	8.0%

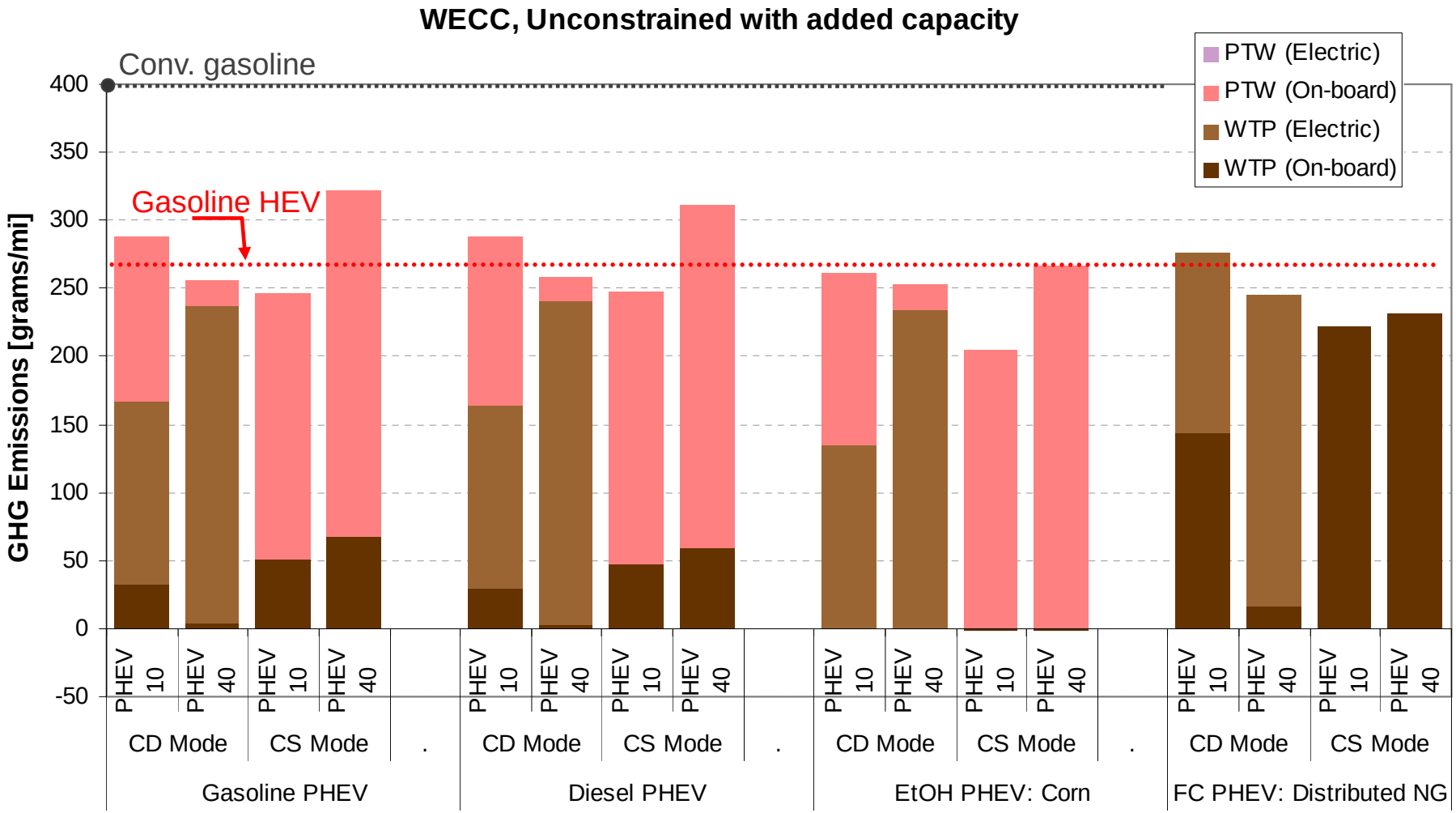
WTW Simulation Results: Details of CD Operation Results

CD vs. CS Operation: WTW Total Energy Use



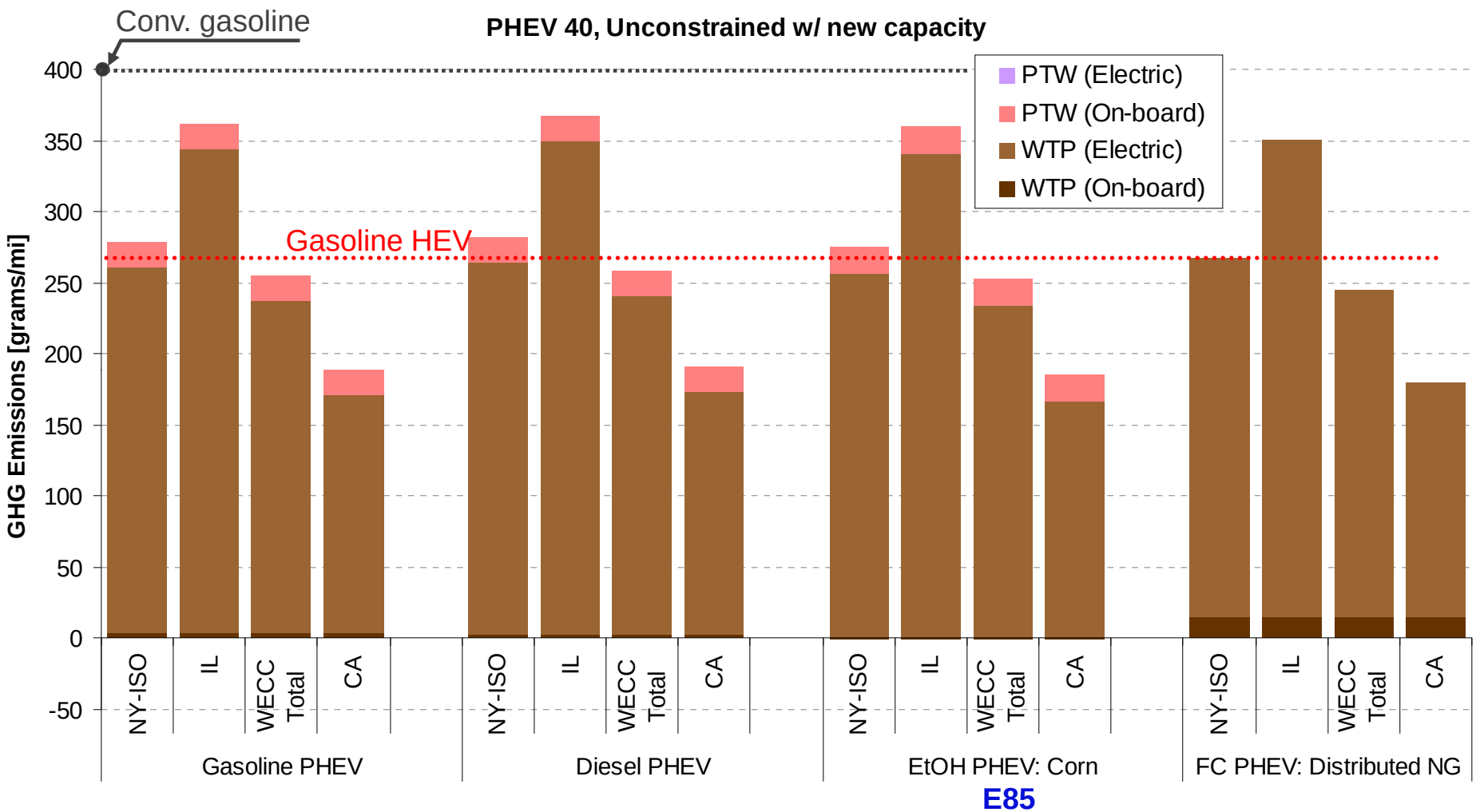
- Higher WTW efficiency in CD mode for series design (PHEV 40) compared to split design (PHEV10)
- Lower WTW efficiency in CS mode for series design (PHEV 40) compared to split design (PHEV10)

CD vs. CS Operation: WTW GHG Emissions



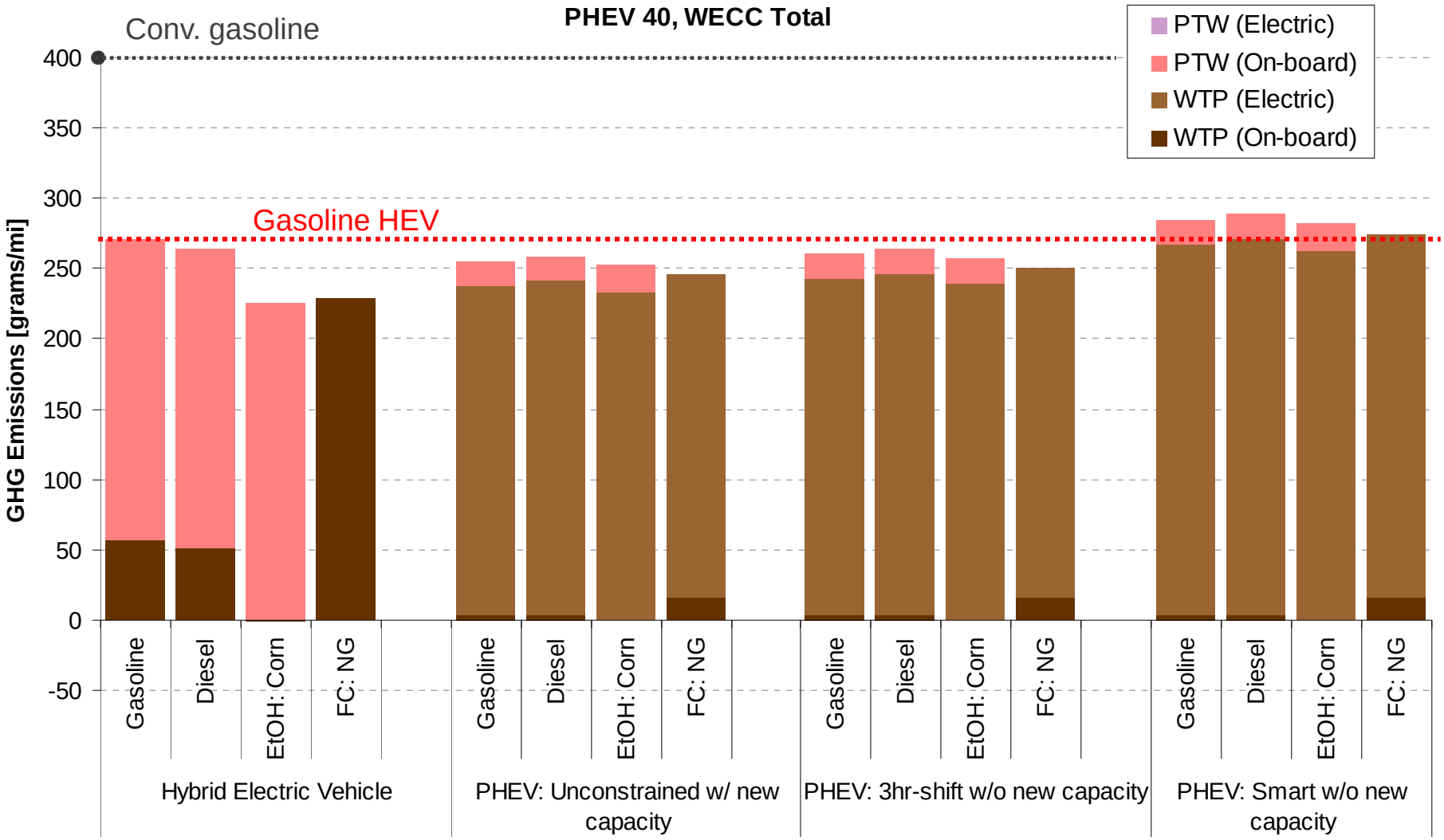
Less GHG emissions in CD mode and higher GHG emissions in CS mode for PHEV40 compared to PHEV10

CD Operation Among Regions: WTW GHG Emissions



- Marginal generation mix is key for GHG emissions
- Impact of higher generation efficiency in WECC compared to NY is shown

CD Operation Under Three Charging Scenarios: WTW GHG Emissions



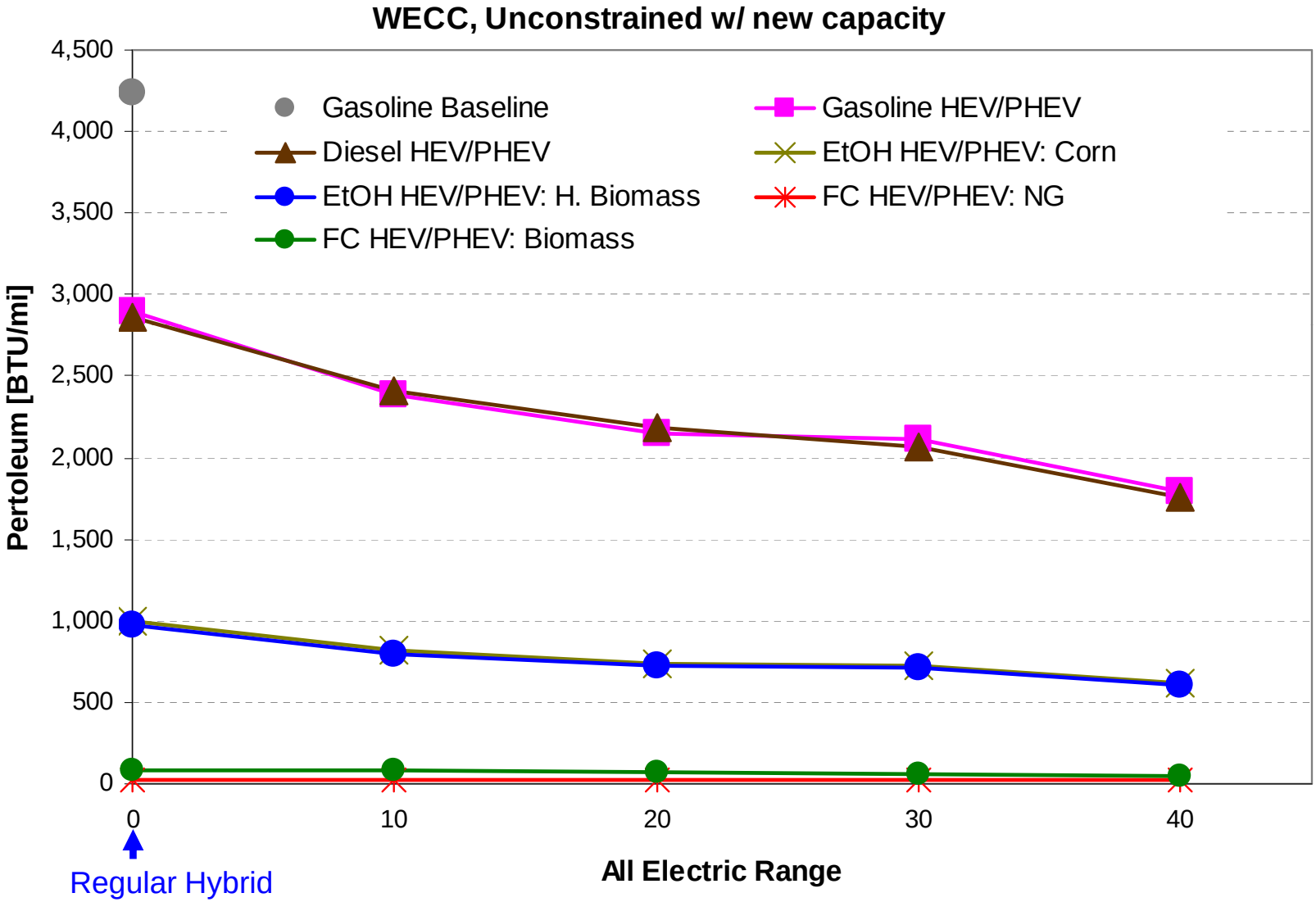
- More GHG emissions from smart charging compared to unconstrained case

Summary: Key Factors Impacting WTW Results of PHEVs in CD Operation

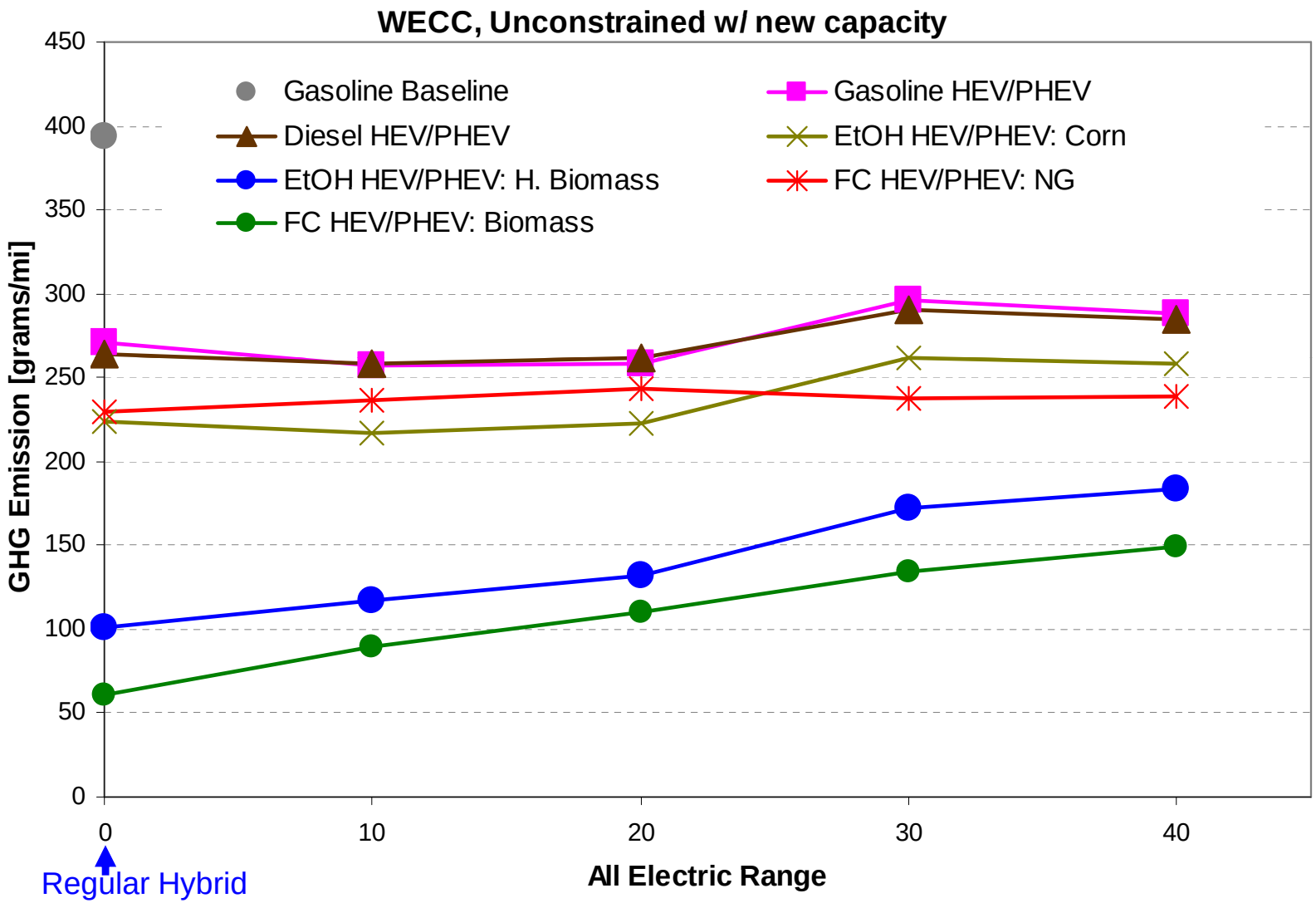
- Vehicle's design configuration: AER, split vs. series
- Electricity consumption (Wh/mi) and on-board fuel economy (mpgge) during CD blended mode of operation
- On-road fuel economy adjustment factor (70% for CD electric and on-board operation)
- Battery charging efficiency (85%)
- Electricity transmission losses (about 7%-10%)
- Power generation efficiency
  - Negative impact from reduced capacity factor
- Marginal electricity generation mix

WTW Results: Combined CD and CS Operation For All AERs

WTW Petroleum Energy Use: Comparison of Technology and All Electric Range

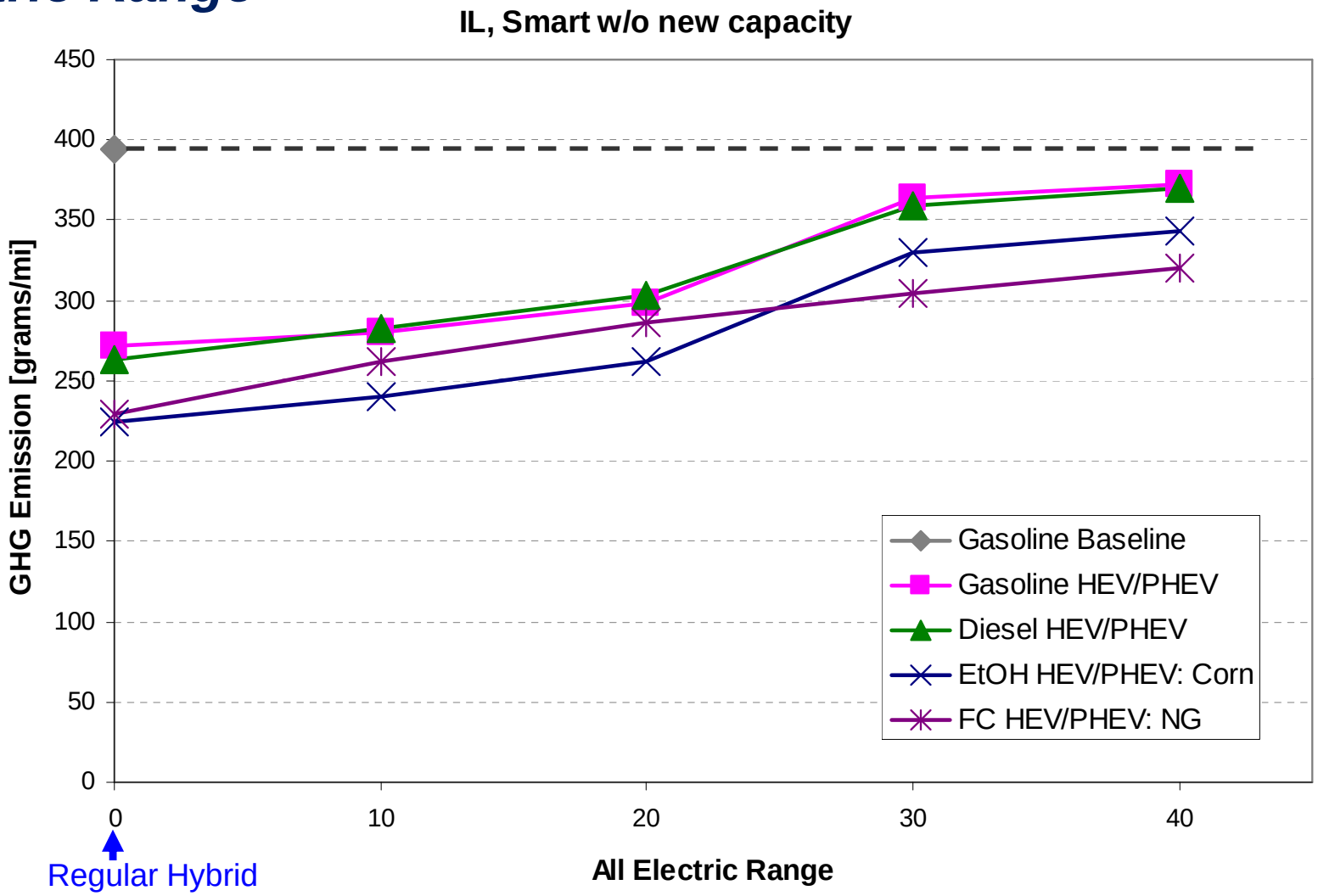


WTW GHG Emissions: Comparison of Technology and All Electric Range



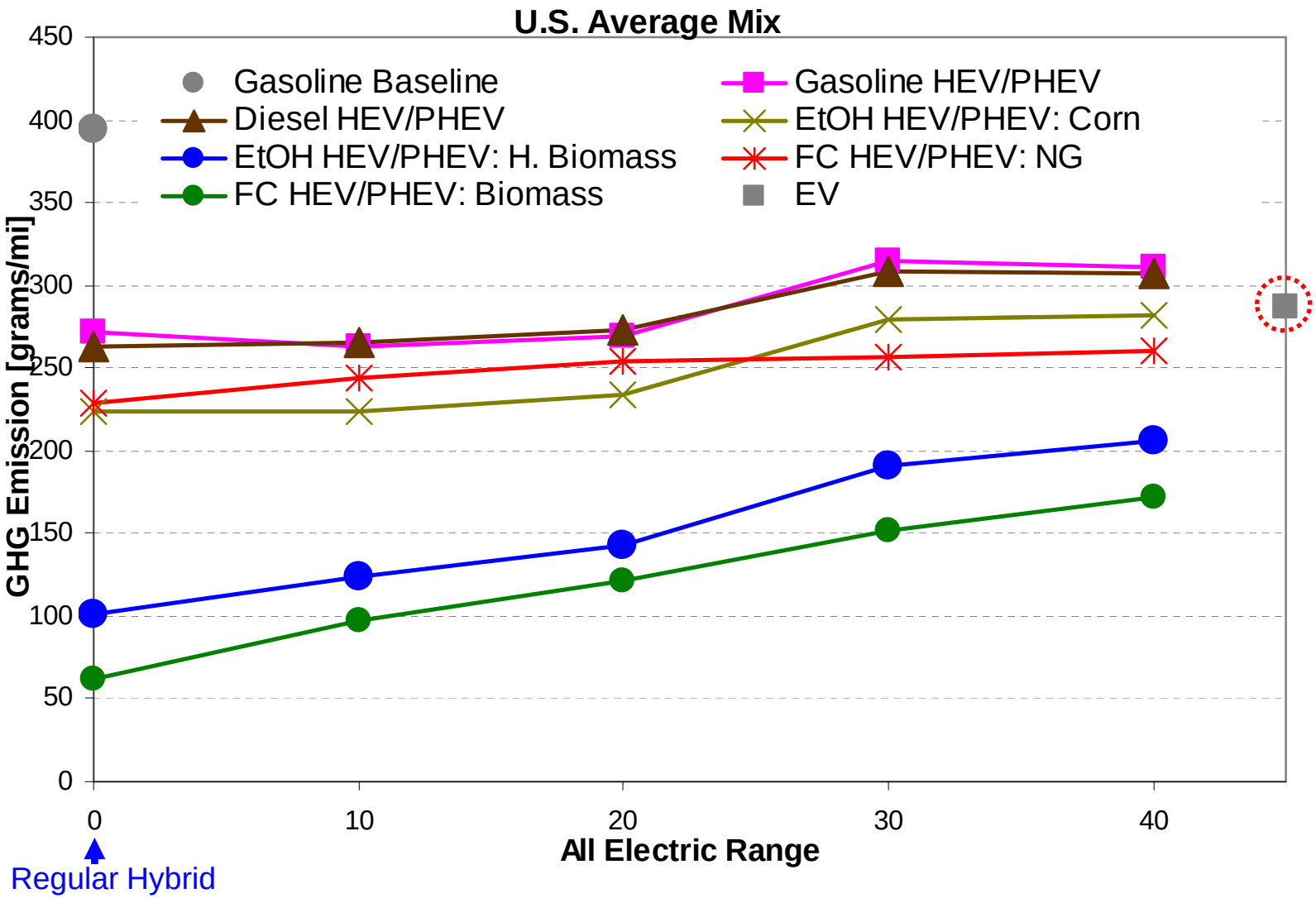
***Note**: The generation mix for the aggregate load of all PHEVs (with different AERs) is used to characterize the performance of individual AER of PHEVs*

WTW GHG Emissions: Comparison of Technology and All Electric Range

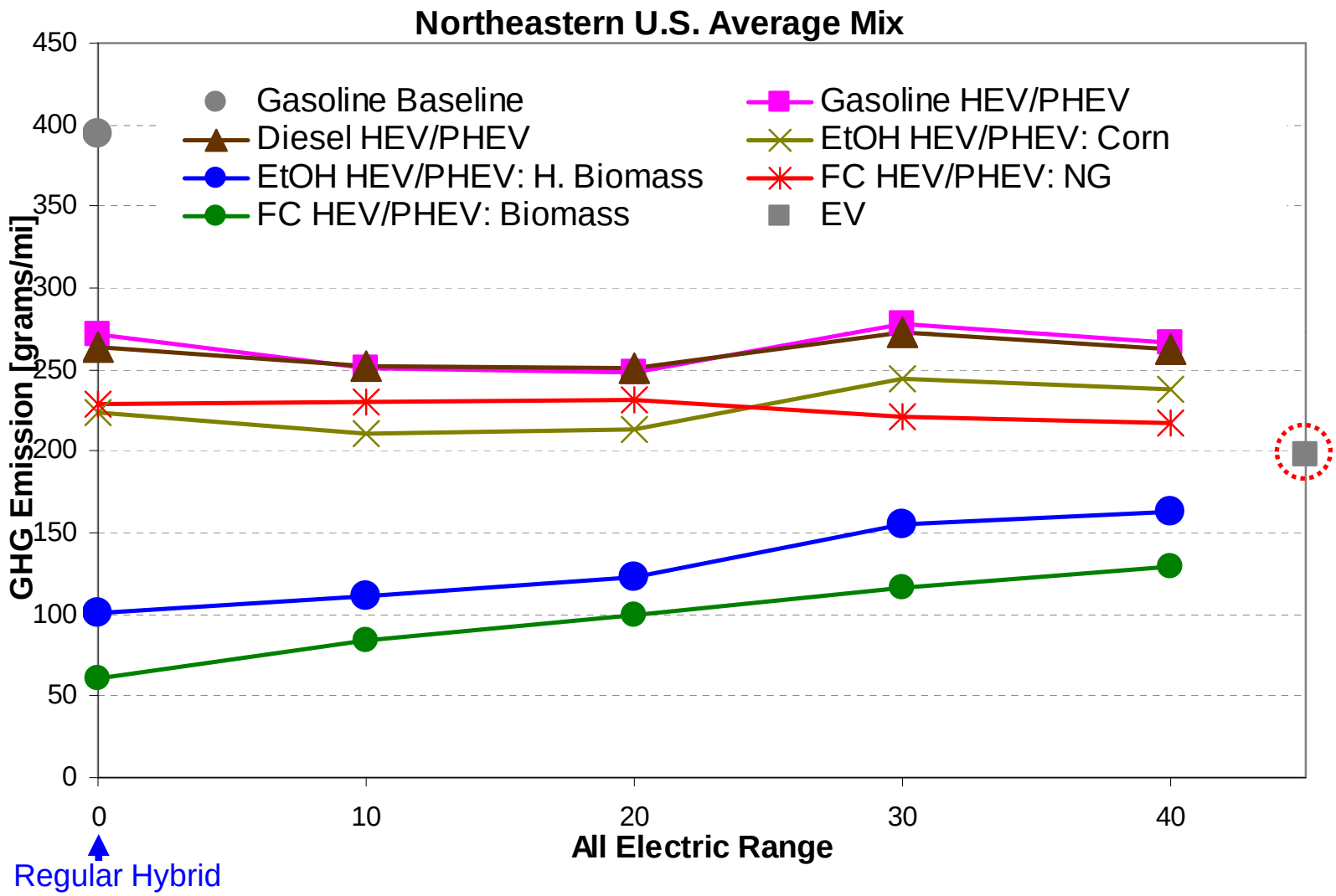


***Note**: The generation mix for the aggregate load of all PHEVs (with different AERs) is used to characterize the performance of individual AER of PHEVs*

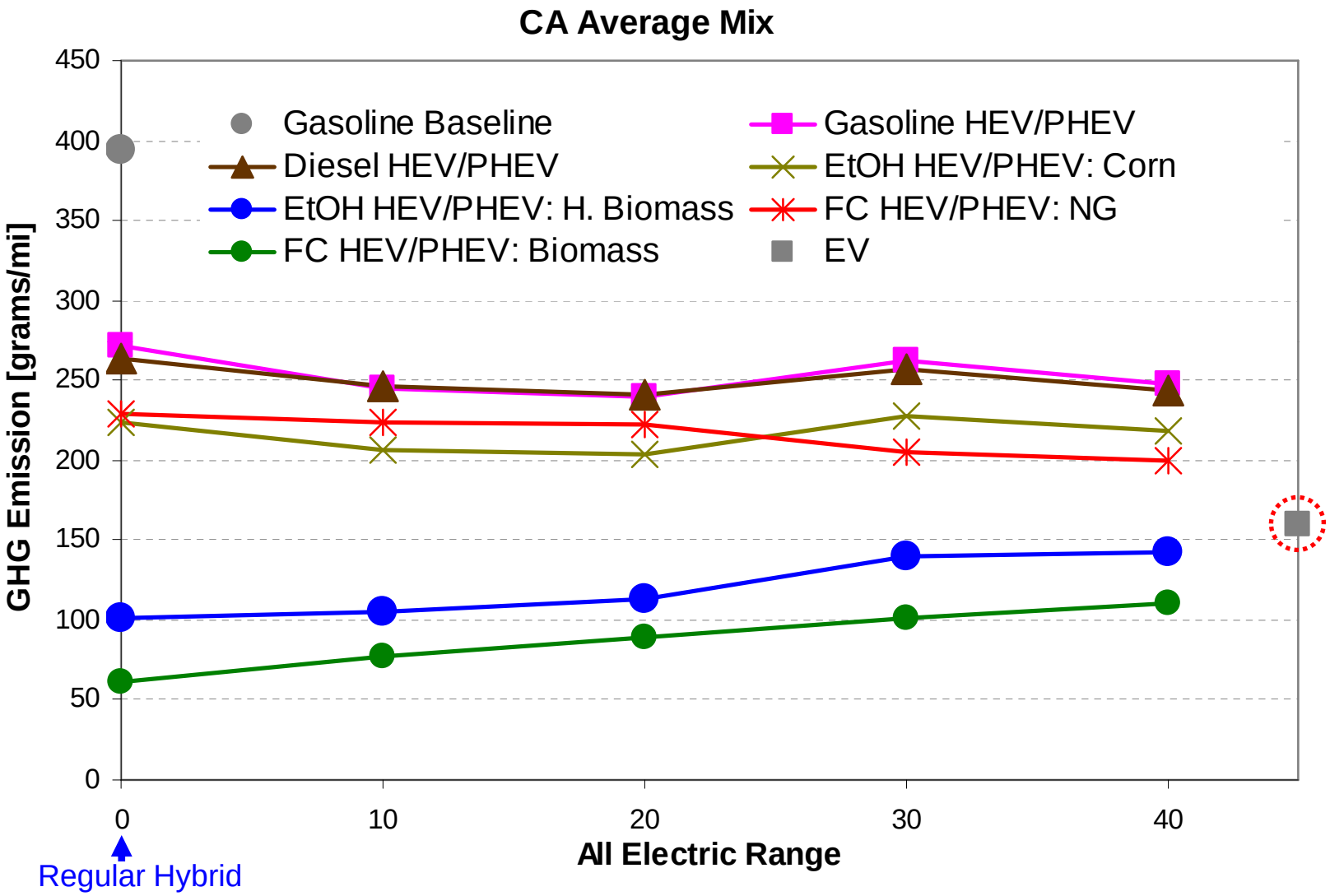
WTW GHG Emissions: Comparison of Technology and All Electric Range



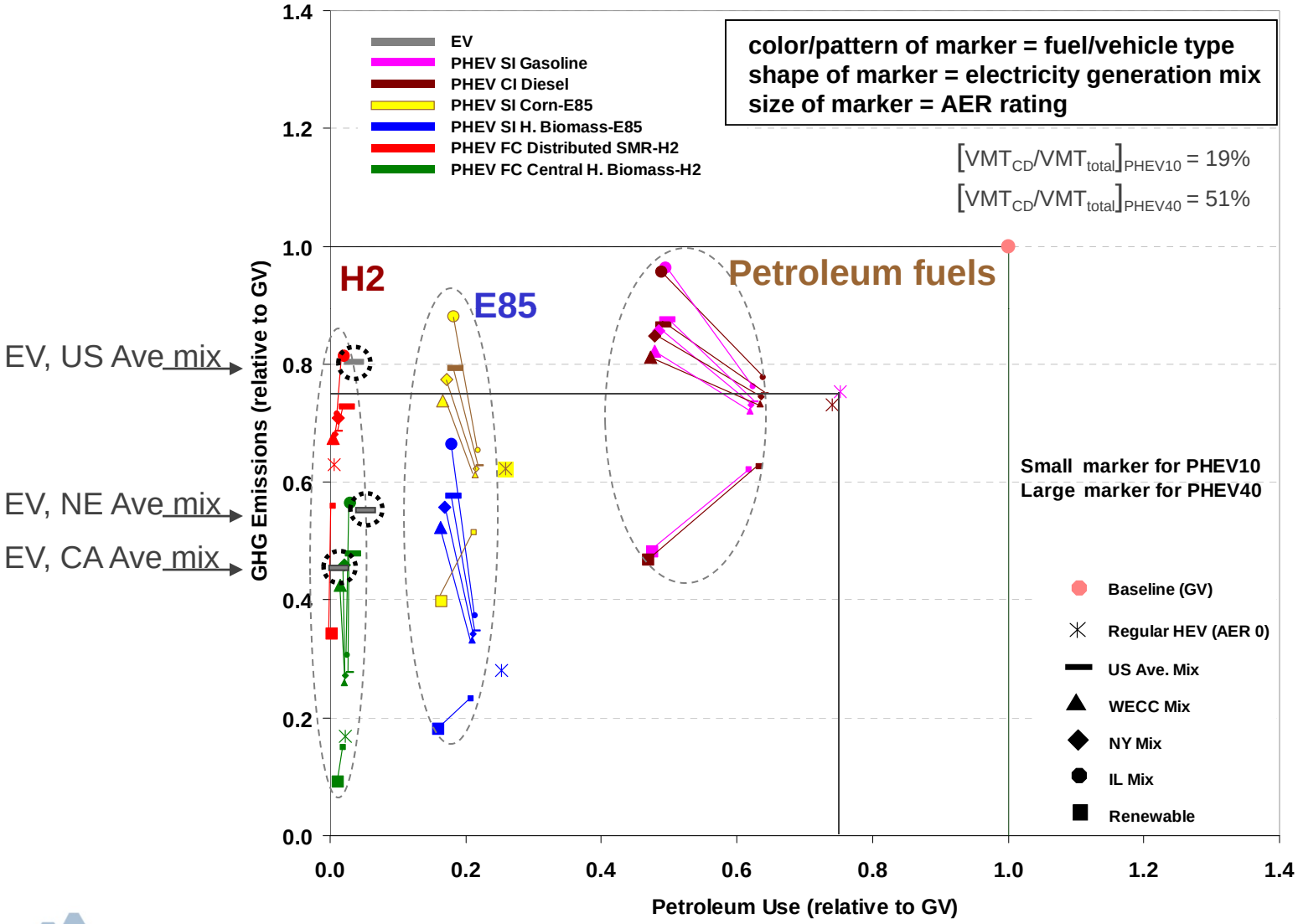
WTW GHG Emissions: Comparison of Technology and All Electric Range



WTW GHG Emissions: Comparison of Technology and All Electric Range



Summary of Petroleum Energy and GHG Effects of All Evaluated Options: Unconstrained Charging Scenario



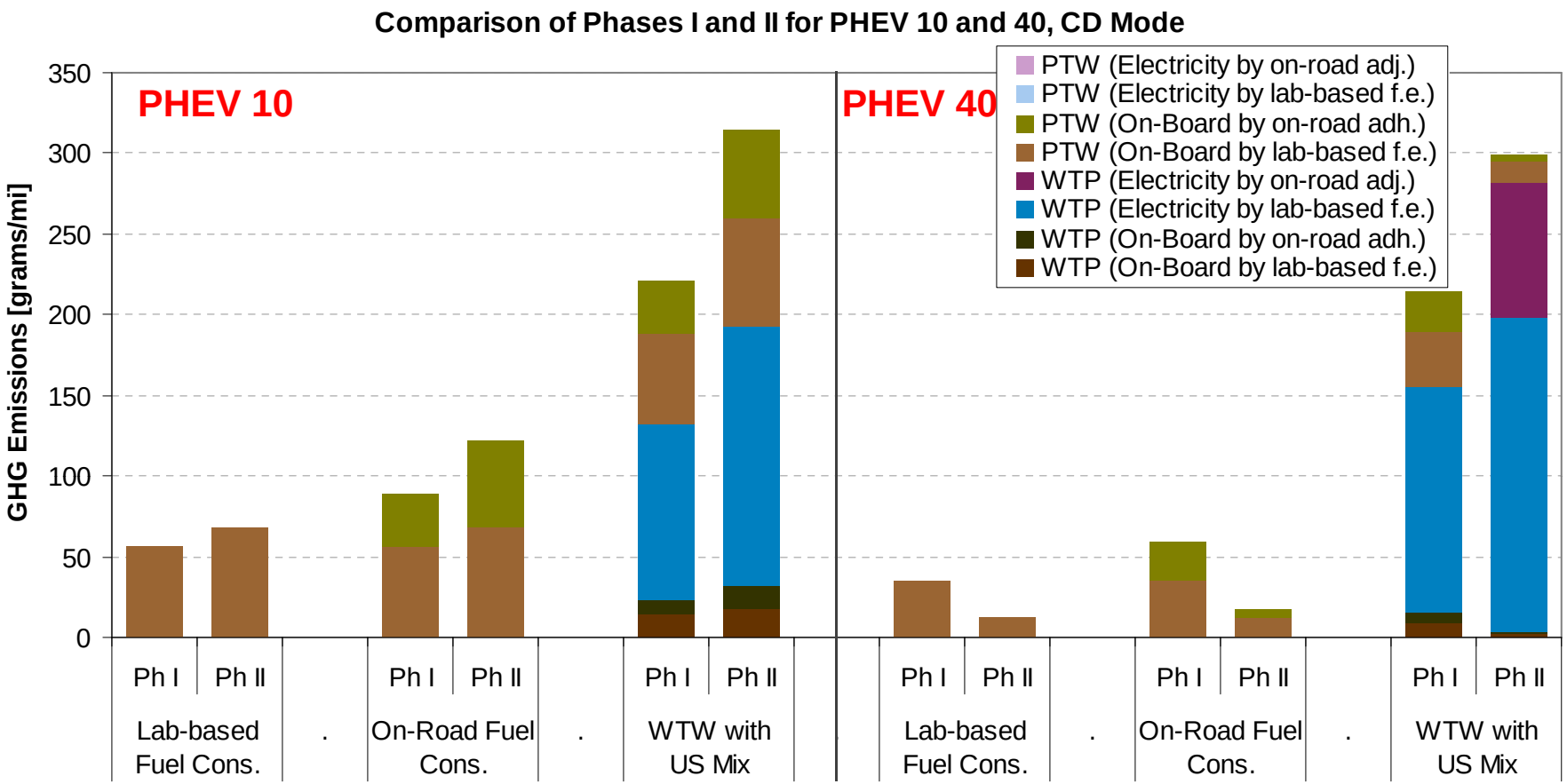
Concluding Remarks

- Adjusting fuel economy for EV and CD mode of PHEV significantly impacts WTW results
  - 70% adjustment of fuel economy for EV and PHEV in CD operation; any technology opportunity to reduce on-road degradation for electric drive technologies?
- Series design of PHEV consumes more electricity and less fuel in CD mode compared to split PHEV, but with lower fuel economy in CS mode
  - Series PHEV produces less GHG emissions in CD mode compared to split hybrid in all regions (except for biomass-based fuels)
  - Split PHEV produces less GHG emissions in CS mode compared to series hybrid in all regions
- The WTW efficiency of the electric path in CD mode is lower compared to regular gasoline HEV
  - Marginal generation mix and efficiency for PHEV recharge is crucial for GHG emissions
  - Lower power generation efficiency as a result of lower capacity factor for newly added NGCC generation units; can the efficiency be increased in the future when larger PHEV penetration occurs?
  - Do PHEVs offer opportunity for non-dispatchable renewable power?
- With the small PHEV penetration simulated, three charge scenarios have small (or negative) effects environmentally; they are probably more for economics of utility system operation
- Significant import/export of electricity may alter the baseline and marginal generation mixes for the regional loads significantly (e.g., CA and rest of WECC)
- We considered three charging scenarios; additional scenarios could be examined
  - CO2 price under a carbon cap and trade program
  - PHEV-induced renewable power dispatch
  - Detailed design of a smart charge scenario

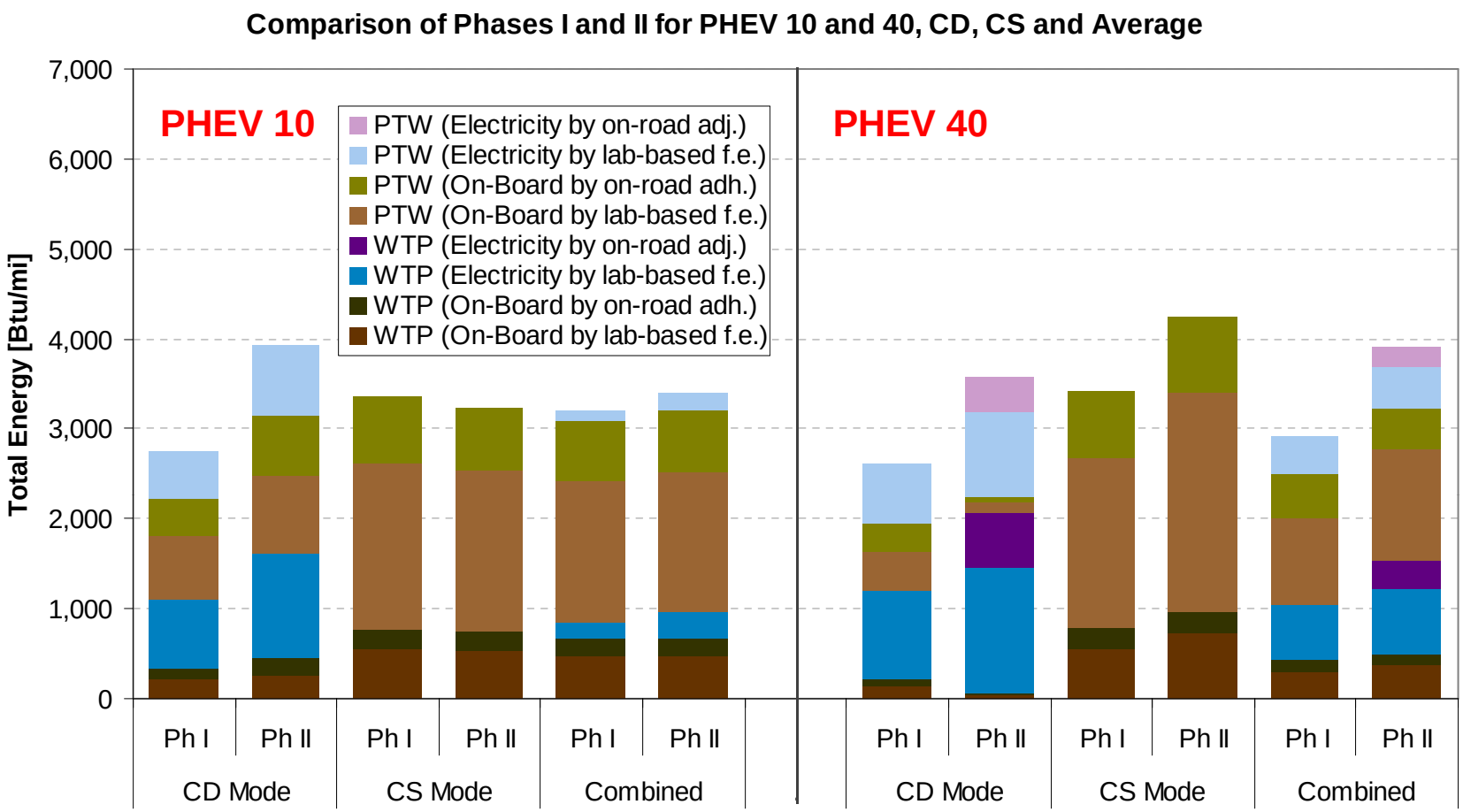
Acknowledgment

This work has been sponsored by Fred Joseck, Office of Fuel Cells and Hydrogen Infrastructure Technologies, DOE. We are thankful for his continued support.

Additional Slides for Comparison Between Phase 1 and Phase Reuslts



In addition to the lab-based fuel economy difference, the **70% on-road adjustment** is the key factor for CD mode of operation. The on-road adjustment increases the WTW GHG emissions of CD model by 25% and 38% for PHEV 10 and PHEV 40, respectively.

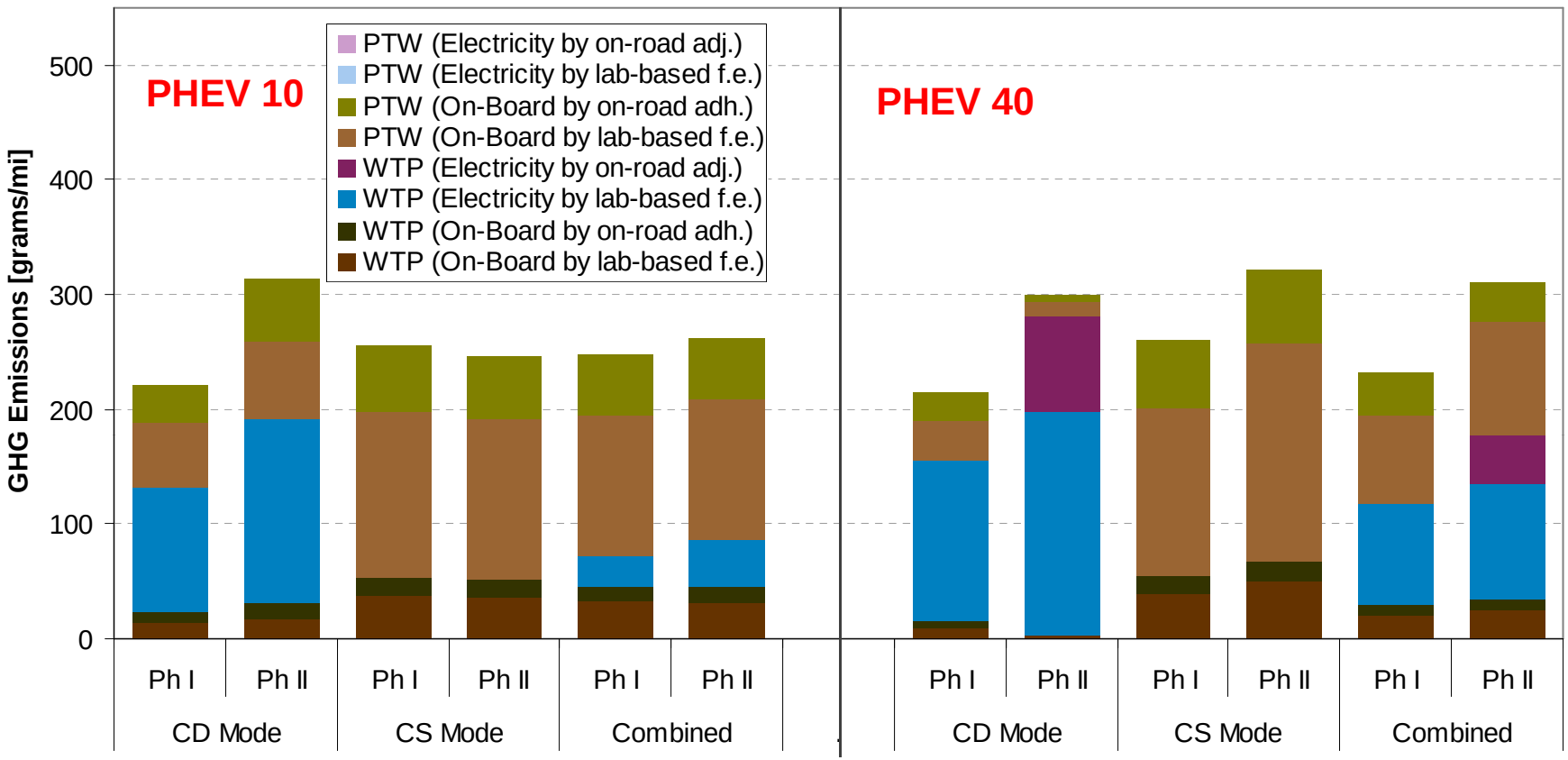


$[VMT_{CD}/VMT_{Total}]_{PHEV10,\ Phase\ I} = 23\%$
$[VMT_{CD}/VMT_{Total}]_{PHEV10,\ Phase\ II} = 25\%$

$[VMT_{CD}/VMT_{Total}]_{PHEV40,\ Phase\ I} = 63\%$
$[VMT_{CD}/VMT_{Total}]_{PHEV40,\ Phase\ II} = 51\%$

When CD and CS modes are combined, the impact of 70% on-road adjustment is reduced depending on the **VMT share of CD mode** of operation. The on-road adjustment increases the WTW total energy by 5% and 15% for PHEV 10 and PHEV 40, respectively.

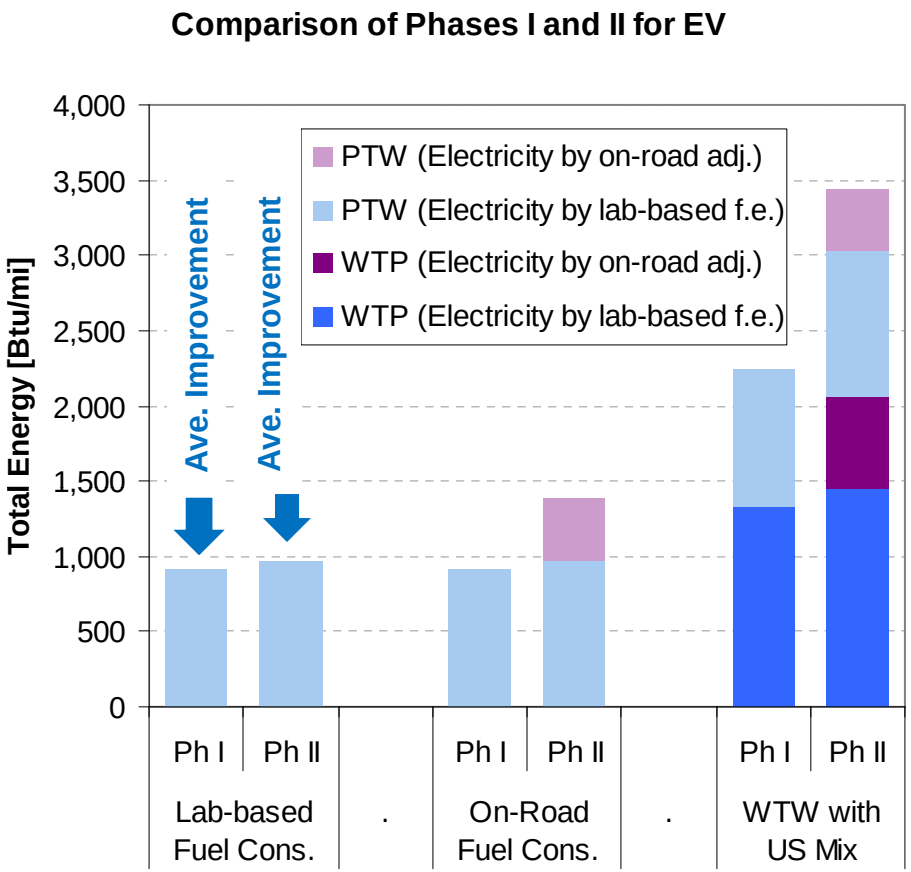
Comparison of Phases I and II for PHEV 10 and 40, CD, CS and Average

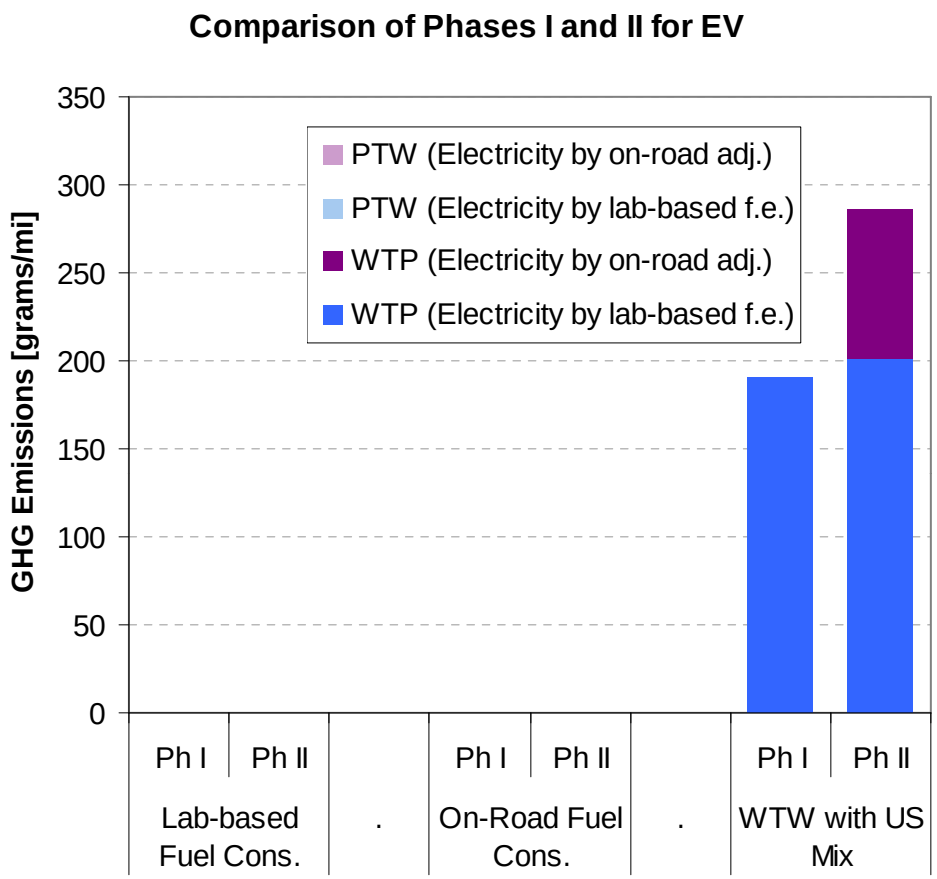


$[VMT_{CD}/VMT_{Total}]_{PHEV10,\ Phase\ I} = 23\%$
$[VMT_{CD}/VMT_{Total}]_{PHEV10,\ Phase\ II} = 25\%$

$[VMT_{CD}/VMT_{Total}]_{PHEV40,\ Phase\ I} = 63\%$
$[VMT_{CD}/VMT_{Total}]_{PHEV40,\ Phase\ II} = 51\%$

When CD and CS modes are combined, the impact of 70% on-road adjustment is reduced depending on the **VMT share of CD mode** of operation. The on-road adjustment increases the WTW GHG emissions by 5% and 16% for PHEV 10 and PHEV 40, respectively.





The **70% on-road adjustment,** as well as **the lab-based fuel economy**, is the key factor for EVs. The on-road adjustment increases the WTW total energy and GHG emissions by 43%.